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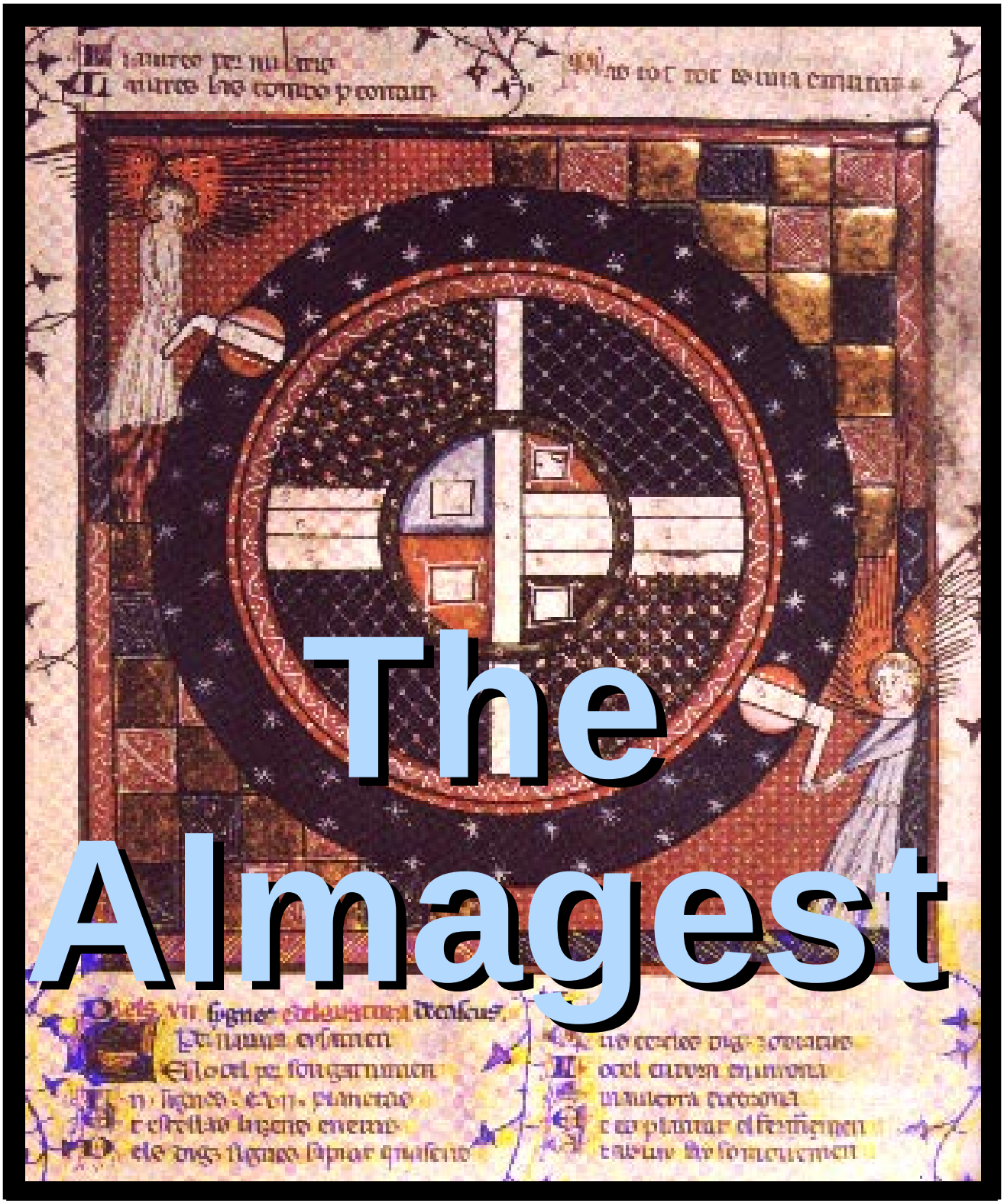

The Almagest

Vol. 2 - Ptolemy 0.7 Programmer's Manual

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Current Sponsors

The Ptolemy project is supported by the Defense Advanced Research Projects Agency (DARPA), the State of California MICRO program, and the following companies: The Alta Group of Cadence Design Systems, Hewlett Packard, Hitachi, Hughes Space and Communications, LG Electronics, NEC, Philips, and Rockwell.

The Ptolemy project is an ongoing research project focusing on design methodology for heterogeneous systems. Additional support for further research is always welcome.

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About the Cover

The image on the cover is from a fourteenth century Provençal illuminated manuscript at the British Library. It depicts angels cranking a celestial gear that activates planetary spheres. The earth is motionless, at the center.

Chapter 1. Extending Ptolemy — Introduction

Authors: *Christopher. Hylands*
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José Luis Pino

1.1 Introduction

Ptolemy is extensible in the following ways:

- New galaxies can be defined. We do not view this as a programming task, so it is explained in the *User's Manual* rather than in this *Programmer's Manual*.
- Customized simulation builders and controllers can be created using the `ptcl` interpreted command language. This language is also covered in the *User's Manual*.
- New functional blocks (stars) can be added to any of the Ptolemy domains. These blocks can be dynamically linked with either `ptcl` or `pigi`.
- New code generation blocks can be added to existing synthesis domains.
- Stars with customized user interfaces and displays can be created using Tcl/Tk.
- New simulation and design-flow managers (called targets) can be created.
- New domains with new models of computation can be created.

This volume explains how to accomplish most of the above. The *Kernel Manual*, volume 3 of *The Almagest*, supplements this volume with a detailed listing of all of the classes in the Ptolemy kernel and in the code generation kernel. The sophisticated user, however, who is extending the system in nontrivial ways, will wish to refer to the source code as the ultimate, most complete documentation.

In this volume, we assume familiarity with the terminology and use of Ptolemy. Refer to the *User's Manual*, and particularly to the glossary contained therein for assistance. We also assume you are familiar with the overall organization of the Ptolemy software, as described in *User's Manual*.

1.2 File Organization

Ptolemy is distributed with source code. The complete distribution even includes the compiler we use (g++, from the Free Software Foundation), Tcl/Tk, and `vem`, programs that were developed quite independently, but upon which Ptolemy relies. The distribution also includes a large number of demonstrations. Perusing the demonstrations can be an excellent way to get familiar with the system. Perusing the source code is by far the best way to understand the system. At a minimum, anyone wishing to write new stars should read the source

code for a few of the built-in stars.

1.2.1 Ptolemy environment variables

The root of the Ptolemy tree is often installed in the home directory of a fictitious user called `ptolemy`. If the installation follows this model at your site, you can find the Ptolemy code with the following command:

```
cd ~ptolemy
```

If your installation does not have a user named `ptolemy`, then you must find out where your system administrator has installed the system, and set an environment variable called `PTOLEMY` to point to this directory. For instance, if your system administrator installed Ptolemy in `/users/ptolemy`, then you should issue the following command:

```
setenv PTOLEMY /users/ptolemy
```

`$PTARCH` is an environment variable representing the architecture on which you are running, and has one (or more) of the following values: `sun4`, `sol2`, or `hppa`, for Sun (under Sun O/S), Sun (under Solaris 2.X), and HP machines respectively. There are a few other possible values for the `PTARCH` variable as well. There might be variations like `sol2.cfront` or `hppa.cfront` to store an object tree created by the Cfront C++ compiler or some other non-g++ compiler.The script `$PTOLEMY/bin/ptarch` will return the architecture of the machine on which it is run. For example, if you were on a machine running SunOS4.1.3, you would type:

```
setenv PTARCH sun4
```

You can use the following fragment in your `.cshrc` file to set `$PTOLEMY` and `$PTARCH`. The `$PTOLEMY/.cshrc` file contains the fragment below and many other csh setup commands you may find useful.

```
setenv PTOLEMY /users/ptolemy
if (! $?$PTARCH) setenv $PTARCH ` $PTOLEMY/bin/ptarch`
set path = ( $PTOLEMY/bin $PTOLEMY/bin.$PTARCH $path )
```

Note that if you are using a prebuilt Gnu compiler that you obtained from the Ptolemy project, you must either place the Ptolemy distribution at `/users/ptolemy`, or you must set certain environment variables so that the Gnu compiler can find the necessary pieces of itself. Appendix A, Installation and Troubleshooting of the Ptolemy *User's Manual* discusses these variables in detail. The variables change with different releases of the compilers, so we do not document them here. The User's Manual also documents other useful environment variables, such as `LD_LIBRARY_PATH`.

For every directory under the `src` tree (see figure 1-2) that contains source code that is compiled, there is a corresponding directory under the `obj.$PTARCH` tree. Many developers find it convenient to set the following aliases:

```
alias srcdir ‘cd `pwd | sed “s?/obj.$PTARCH/?/src/?”`’
alias objdir ‘cd `pwd | sed “s?/src/?/obj.$PTARCH/?”`’
```

For your convenience, these can be found in the file `$PTOLEMY/.alias`. They make it easy to move between the source directory and the corresponding object directory. For example, if you are running on a Sun machine running Solaris 2.4,

```
% cd $PTOLEMY/src/kernel
% pwd
/users/ptolemy/src/kernel
% objdir
% pwd
/users/ptolemy/obj.sol2/kernel
% srcdir
% pwd
/users/ptolemy/src/kernel
%
```

1.2.2 Directory Structure

The documentation (usually) refers to the root of the Ptolemy directory tree as `$PTOLEMY`, but occasional slips will refer to `~ptolemy`. Below this root, you can find the directories indicated in figure 1-1.

The `src` directory is key to much of what this volume deals with. Its structure is shown in figure 1-2. Within the `src` directory, the `kernel` directory is most important. It contains all the classes that define what Ptolemy is. Second most important is the `domains` directory. Its structure is shown in figure 1-3. This directory contains one subdirectory that defines each of the domains distributed with Ptolemy. Each domain directory contains at least the subdirectories shown in figure 1-4. If you are going to write stars for the SDF domain, for example, then you would be well advised to look at a few examples contained in the directory `$PTOLEMY/src/domains/sdf/stars`.

The directory `$PTOLEMY/mk` contains master makefiles that are included by other makefiles (The makefile `include` directive does this for us). `$PTOLEMY/mk/config-$PTARCH.mk` refers to the makefile for the architecture `$PTARCH`. For instance, `$PTOLEMY/mk/config-sun4.mk` is the makefile that contains the sun4 specific details.

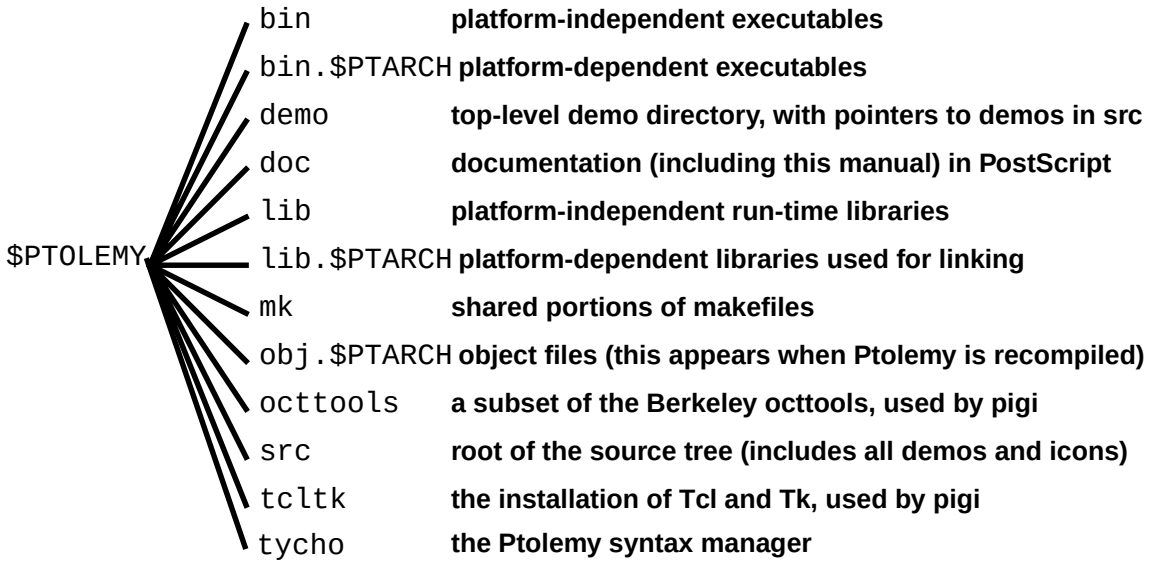

FIGURE 1-1: Structure of the home directory of the Ptolemy installation ($PTOLEMY).

When you cd to `$PTOLEMY` and type `make`, `$PTOLEMY/makefile` contains a rule that checks to see if the directory `$PTOLEMY/obj.$PTARCH` exists. If this directory does not exist, then make runs the command `csh -f MAKEARCH`, where `MAKEARCH` is a C shell script at `$PTOLEMY/MAKEARCH`. `MAKEARCH` will create the necessary subdirectories under `$PTOLEMY/obj.$PTARCH` for `$PTARCH` if they do not exist.

We split up the sources and the object files into separate directories in part to make it easier to support multiple architectures from one source tree. The directory `$PTOLEMY/obj.$PTARCH` contains the platform-dependent object files for a particular architecture. The platform-dependent binaries are installed into `$PTOLEMY/bin.$PTARCH`, and the libraries go into `$PTOLEMY/lib.$PTARCH`. Octtools, Tcl/Tk, and Gnu tools have their own set of architecture-dependent directories.

The makefiles are all designed to be run from the `obj.$PTARCH` tree so that object files from different platforms are kept separate (when you run `make` in the `$PTOLEMY` top level, the appropriate `obj.$PTARCH` tree is selected for you automatically).

We are able to have separate object and source directories by using the `make` program's `VPATH` facility. Briefly, `VPATH` is a way of telling `make` to look in another directory for a file if that file is not present in the current directory. For more information, see the Gnu `make` documentation, in Gnu Info format files in `$PTOLEMY/gnu/common/info/make-*`.

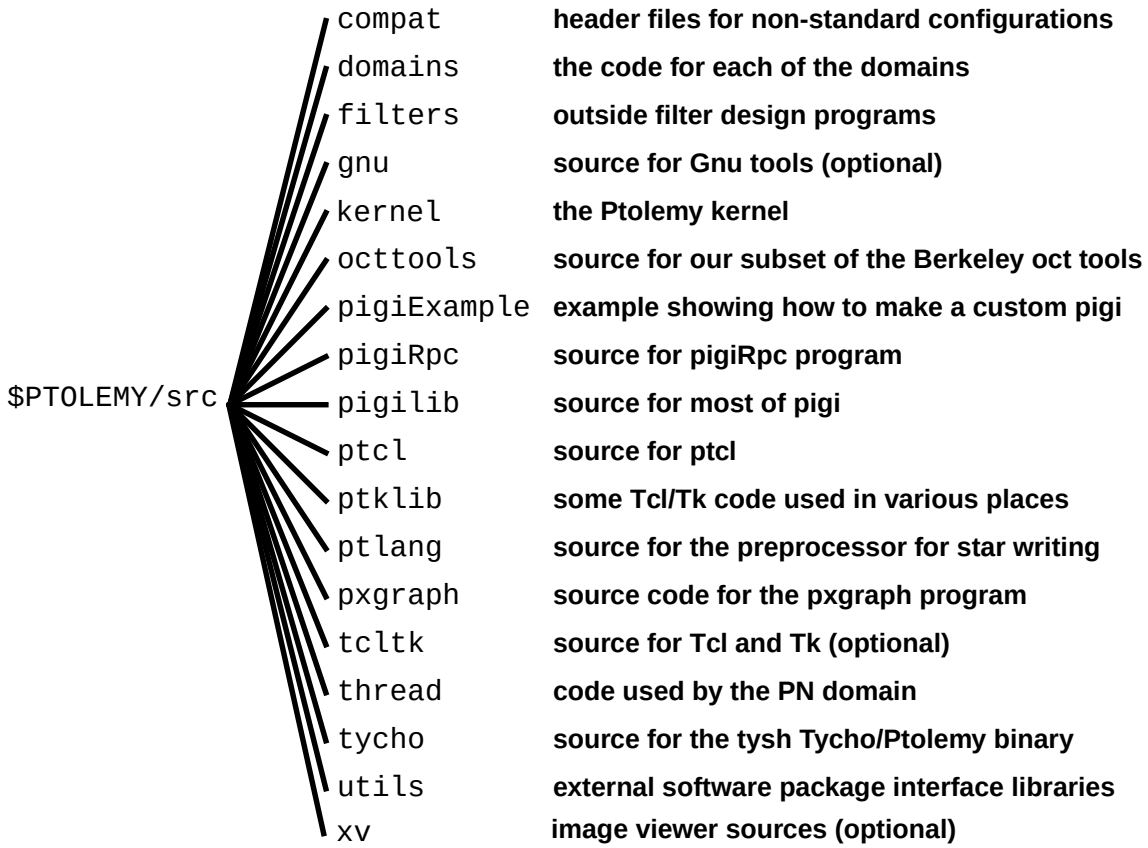

FIGURE 1-2: The structure of the $PTOLEMY/src directory

There are three primary Ptolemy binaries:

`pigiRpc` The graphical version that uses `vem` as a front end. `pigiRpc` contains an interface to Octtools, the package that is used to store facets. When you run `pigi`, you actually run a script called `$PTOLEMY/bin/pigiEnv.csh` which calls `vem` which, in turn, starts up `pigiRpc`.

`ptcl` A prompt version that contains most of the functionality in `pigiRpc` not including the Tk stars. `ptcl` does not contain an interface to Octtools

`tysh` The Tycho shell version, which is similar to `pigiRpc`, except that `tysh` does not contain an interface to Octtools. Note that Tycho can be run from a basic `itkwish` binary that contains no Ptolemy functionality.

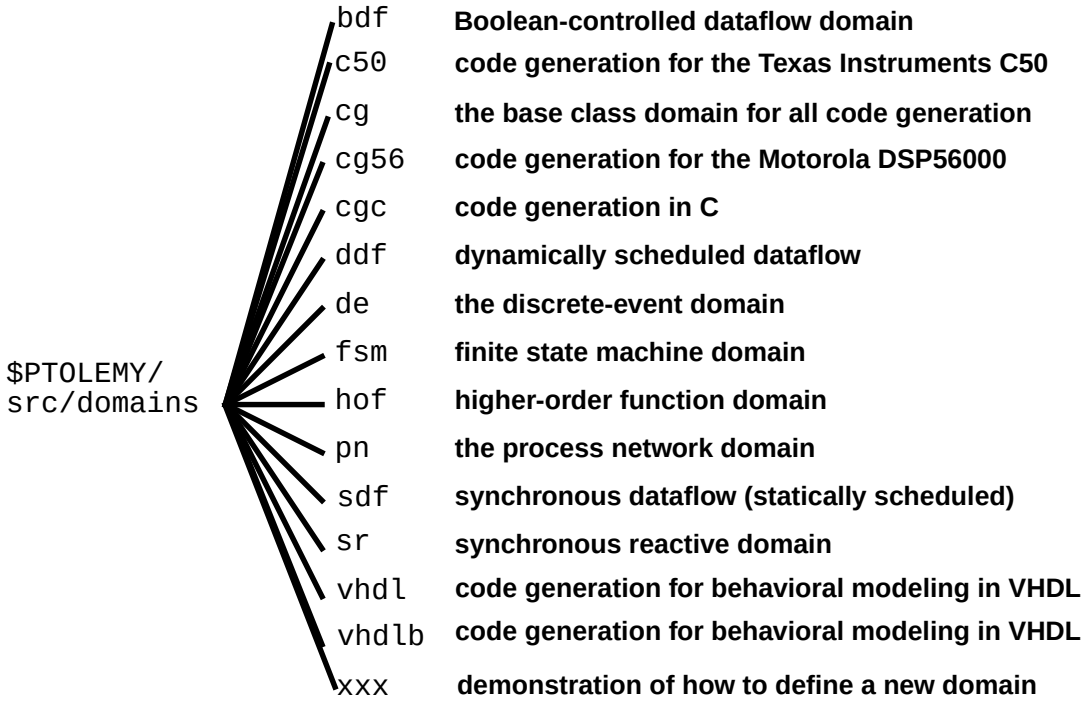

FIGURE 1-3: The structure of the $PTOLEMY/src/domains directory.

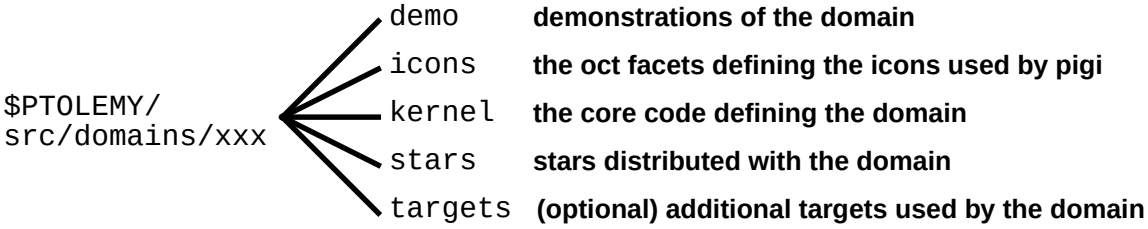

FIGURE 1-4: The structure of a typical domain directory within $PTOLEMY/src/domains.

Each of the three binaries above has three different versions that contain different functionality. Below we only list the different version of `pigiRpc`, but `ptcl` and `tysh` have similar versions.

`pigiRpc`	This binary contains all of the domains, so it is the largest binary.
`pigiRpc.ptrim`	This binary contains SDF, DE, BDF, DDF and CGC domains only.
`pigiRpc.ptiny`	This binary contains SDF (no image stars) and DE domains only.

Each of the above versions can also be built as a `.debug` version that contains debugging information. The file `$PTOLEMY/mk/ptbin.mk` contains rules to build the above binaries in combination with debugging and other features. The file `$PTOLEMY/mk/stars.mk` contains rules that indicate dependencies between domains and other features.

1.3 Creating Custom Versions of pigiRpc

Ptolemy is an extensible system. Extensions can take the form of universes and galaxies, which are viewed by Ptolemy as applications, but they can also take the form of additional code linked to the Ptolemy kernel. New stars can be dynamically linked (see “Writing Stars for Simulation” on page 2-1). Other additional code has to be linked in statically. If you add many of your own stars to the system, you will want these stars to be statically linked as well, so that you do not have to wait for the dynamic linking to complete every time you execute your applications.

The Ptolemy kernel and `vem` (the schematic editor) run in separate Unix processes. The Ptolemy kernel process is called “`pigiRpc`”, while the `vem` process is called “`vem`”. You can create your own version of `pigiRpc` that contains your stars and other extensions permanently linked in.

There are at least three ways to build your own `pigiRpc`, depending on the kind of extensions you are making. The first way uses `src/pigiExample`, and it is intended for users who just need to add new stars. The second and third ways use the `mkPtolemyTree` script and csh aliases and are for users that are creating new domains or making other more extensive changes.

If you want to extend Ptolemy by modifying or adding a new scheduler, target, or even an entire domain, it is recommended that you create a duplicate directory hierarchy. This allows you to experiment with and fully test any changes separately, rather than incorporating them into the “official” version of Ptolemy. This way, your experimentation will not interfere with other Ptolemy users at your site, and your changes will not be overwritten by future installations of Ptolemy releases. It also means that all of the existing makefiles will work without modification because all of the paths specified are relative to the root of the hierarchy.

The most direct way to do this is to copy the entire Ptolemy hierarchy. This could be done with a command such as:

```
cp -r $PTOLEMY ~/ptolemy
```

which would create a copy of the hierarchy in your home directory. Because this method

requires excessive disk space and makes cooperative development difficult, many developers prefer to use symbolic links when creating a duplicate hierarchy. `mkPtolemyTree` and the csh aliases can help you setup these symbolic links.

1.3.1 Creating a pigiRpc that includes your own stars

For those who just want to statically link in their own stars with minimal hacking with makefiles, an example showing how to do this is provided in `$PTOLEMY/src/pigiExample`.

In the example below, we assume that `$PTOLEMY` and `$PTARCH` are set and that you have write permission to the Ptolemy source tree. If you don't have write permission, you can set up a parallel tree with the Unix `ln -s` command. If, for example, the Ptolemy tree was at `/users/ptolemy`, but you wanted to build under `~/pt`, you could do the following to create the directory and create symbolic links for the dot files, like `.cshrc`, and create symbolic links for the other files and directories in the distribution:

```
mkdir ~/pt
cd ~/pt
ln -s /users/ptolemy/* .
ln -s /users/ptolemy/.??* .
setenv PTOLEMY ~/pt
setenv PTARCH ‘$PTOLEMY/bin/ptarch‘
rm obj.$PTARCH src bin.$PTARCH
mkdir -p src src/pigiExample bin.$PTARCH
cd bin.$PTARCH; ln -s /users/ptolemy/bin.$PTARCH
cd ../src; ln -s /users/ptolemy/src/* .
cd pigiExample; cp /users/ptolemy/src/pigiExample/* .
```

You also need to be sure that you have your environment set up properly for the compiler that you are using.

Continuing with our example of how to build a `pigiRpc` that includes your own stars:

1. Build a basic `pigiRpc`. `PigiRpc` depends on `.o` files under `$PTOLEMY/obj.$PTARCH`, so you must do a basic build. To build all the `.o` files, type:

   ```
   cd $PTOLEMY; make install
   ```

   The complete build process can take upwards of three hours. If you use an `override.mk` file, you can reduce the build time by building only the functionality you need. See “Using mkPtolemyTree to create a custom Ptolemy trees” on page 1-9 for more information.

2. Edit `$PTOLEMY/src/pigiExample/make.template`. Add your stars to `LOCAL_OBJS` and `PL_SRCS`.

3. `cd` to `$PTOLEMY/obj.$PTARCH/pigiExample` and type:

   ```
   make depend
   ```

   to update the `makefile` from the `make.template`. You will see messages something like:

```
makefile remade -- you must rerun make.
exit 1
make: *** [makefile] Error 1
```

This is normal and you may safely ignore the error message.

4. While still in `$PTOLEMY/obj.$PTARCH/pigiExample`, type

   ```
   make
   ```

   This will create a version of the `pigiRpc` executable with your own stars statically linked in. If later you add a new star, you should modify the symbols `OBJS` and `PLSRCS` in `make.template` to include it, and repeat the above procedure.

5. If you built your `pigiRpc` with `SDFMyStar.o`, you can test your `pigiRpc` by starting up with:

   ```
   pigi -rpc $PTOLEMY/obj.$PTARCH/pigiExample/pigiRpc $PTOLEMY/
   src/pigiExample/init.pal
   ```

   and then run the ‘wave’ universe. If you want to have the binary you just built be the default binary for yourself, you can set your `PIGIRPC` environment variable to the name of the binary you just built:

   ```
   setenv PIGIRPC $PTOLEMY/obj.$PTARCH/pigiExample/pigiRpc
   ```

   Next time you start `pigi`, your new executable will be used instead of the standard one. To revert to using the installed `pigiRpc`, just type

   ```
   unsetenv PIGIRPC
   ```

6. If you want your `pigiRpc` to be the default `pigiRpc`, you can install it in `$PTOLEMY/bin.$PTARCH`, but this will wipe out whatever `pigiRpc` is in that directory

With the same makefile, you can make a version of the `pigiRpc` program that has debug symbols. Just type:

```
make pigiRpc.debug
```

To use this, assuming the Gnu debugger `gdb` is in your path, specify the executable as follows:

```
setenv PIGIRPC \
       $PTOLEMY/obj.$PTARCH/pigiExample/pigiRpc.debug
```

assuming your executable is in `$PTOLEMY/obj.$PTARCH/pigiExample/`. Then start `pigi` as follows:

```
pigi -debug
```

To revert to using the installed `pigiRpc`, just type

```
unsetenv PIGIRPC
```

1.3.2 Creating a pigiRpc with more extensive customizations

If you are extending Ptolemy in nontrivial ways, such as writing a new domain, we

suggest that you create your own copy of the Ptolemy directory tree. You may use symbolic links to the "official" directories if you do not need to modify or work on them. Your new code should be placed in the parallel directory with the other similar Ptolemy subdirectories, using the same directory structure. This way you can reuse the makefiles of similar Ptolemy directories with minimal modifications. After you create your own Ptolemy tree and add your new directories and files, certain Ptolemy makefiles, typically `$PTOLEMY/mk/ptbin.mk` and `$PTOLEMY/mk/stars.mk`, need to be modified to include your own code. Building your own `pigiRpc`, `ptcl` or `tysh` this way requires extensive knowledge of the Ptolemy directory tree structure and makefiles, but if you are doing serious development in Ptolemy, you will need to know this anyway.

Warning: If you have write permission in the directory where Ptolemy is installed, make sure to modify the place where "make install" puts the completed executable, or it will attempt to overwrite the `pigiRpc` in the Ptolemy installation, and other users may be upset with you if you succeed in doing that. (If you are using the makefile from `$PTOLEMY/src/pigiExample`, you do not need to worry about this because "make install" has been removed from that makefile.) The simplest thing to do is to replace the line in the `makefile`:

```
install: makefile $(DESTBIN)
```

with:

```
install: makefile pigiRpc
```

This will leave the `pigiRpc` in whatever directory you make it even if you type:

```
make install
```

1.4 Using mkPtolemyTree to create a custom Ptolemy trees

In Ptolemy 0.6 and later, there are two methods of building custom Ptolemy trees that have a user selected set of domains: csh aliases and the `mkPtolemyTree` script. This section discusses the `mkPtolemyTree` script, see "Using csh aliases to create a Parallel Software Development Tree" on page 1-12 for an alternative method of creating a parallel tree.

In Ptolemy 0.6 and later, the `mkPtolemyTree` script and a user supplied `override.mk` file to create an entire custom object tree. The tree will have copies of all Ptolemy directories on which the customized installation depends. The script will also set up the `override.mk` files needed to build custom `pigiRpc`, `tysh` and `ptcl` binaries. Since `mkPtolemyTree` runs very fast, you may avoid having to recompile the entire Ptolemy tree, which can take 3 hours on a fast workstation.

1.4.1 mkPtolemyTree example

The `mkPtolemytree` command usage is:

`mkPtolemyTree` *`override.mk_file root_pathname_of_new_tree`*

For example, say that you wanted to build a tree that only has the VHDL domain in `~/mypt`.

1. One would create a file called `~/override.mk` that contains:

```
VHDL=1
DEFAULT_DOMAIN=VHDL
```

```
VERSION_DESC="VHDL only"
```

The file $PTOLEMY/mk/ptbin.mk contains a list of the makefile variables that can be set to bring in the various domains.

2. Set $PTOLEMY to point to the Ptolemy distribution, in this example, the Ptolemy distribution is at /users/ptolemy:

   ```
   setenv PTOLEMY /users/ptolemy
   ```

3. Set $PTARCH to the appropriate value:

   ```
   setenv PTARCH '$PTOLEMY/bin/ptarch'
   ```

4. Set the path properly:

   ```
   set path = ($PTOLEMY/bin $PTOLEMY/bin.$PTARCH $path)
   ```

5. Execute the mkPtolemyTree command so that the override.mk file is used to create a custom tree in the ~/mypt directory.

   ```
   mkPtolemyTree ~/override.mk ~/mypt
   ```

In general, you will want to define the variables TK and HOF. Setting TK indicates that you want to include Tcl/Tk extensions to the domains. Setting HOF means that you want to include the higher-order functions domain. The higher-order functions domain is used in many demonstrations to configure stars with multiple portholes and to specify scalable systems. So, adding these make variables in the same override.mk file would make it look like the following:

```
HOF=1
TK=1
VHDL=1
DEFAULT_DOMAIN=VHDL
VERSION_DESC="VHDL only"
```

1.4.2 How mkPtolemyTree works

To accumulate a list of the directories necessary to build a custom tree, $PTOLEMY/src/stars.mk contains a makefile variable named CUSTOM_DIRS. In stars.mk, each feature, such as VHDL adds directories to CUSTOM_DIRS. Also a feature can require sub-features, and the sub-features can add directories to CUSTOM_DIRS. For example, VHDL requires CG, and CG adds more directories to CUSTOM_DIRS.

When you run $PTOLEMY/bin/mkPtolemyTree, the following events occur:

1. From the override.mk file that the user specifies, the script builds a tree with the directories as specified the value of the CUSTOM_DIRS makefile variable.

2. Next, the files in the $PTOLEMY tree are copied over if the directory exists using tar (to save modification times).

3. For each directory specified by CUSTOM_DIRS, we create symbolic links to all the directories that we have not expanded from the $PTOLEMY tree the make.template and makefile symbolic links in the obj directories are set correctly.

4. The `override.mk` file is copied into the new tree as *`NEW_ROOT`*`/mk/override.mk`, where *`NEW_ROOT`* is the root path name of the tree we are constructing.

5. `override.mk` files are constructed that reference *`NEW_ROOT`*`/mk/override.mk` specific to `tysh`, `ptcl` and `pigiRpc`.

6. `make install` is run in *`NEW_ROOT`*`/obj.$PTARCH/` which creates the hard link for the libraries in *`NEW_ROOT`*`/lib.$PTARCH` and builds the custom `tysh`, `ptcl`, and `pigiRpc`.

This new tree has all the symbolic links and directories necessary to act as a full-fledged Ptolemy tree. You should be able to set your `PTOLEMY` environment variable to this new tree and `pigi` will run your custom `pigiRpc` binary.

Currently the Tcl libraries and Tycho are not expanded but are accessible via symbolic links. To have the utility expand the `$PTOLEMY/lib/tcl` directory, add the following line to your `override.mk` file:

```
CUSTOM_DIRS += $(CROOT)/lib/tcl
```

To expand Tycho, consult the Tycho documentation and use the `tylndir` script.

There is no documentation of the variables to pull in each domain yet. In general, it is the standard abbreviation for the domain in capital letter. For example, the Synchronous Dataflow (SDF) domain is `SDF`, the Discrete-Event (`DE`) domain is DE, and so forth. Some of the domains are split up, the entire domain can be brought in by defining *`FOO`*`FULL` (e.g., `SDFFULL` or `CGCFULL`). When defined, they include all of the SDF and CGC functionality, respectively, whereas SDF and CGC include only the basic functionality. The basic version of the SDF domain does not include the image, matrix, Matlab, DSP, and Tcl/Tk stars. If you are attempting to build a pigi that includes the Process Network (PN) domain, then you should add the following to your `override.mk` file.

```
INCLUDE_PN_DOMAIN = yes
```

For a listing of the possible make variables, refer to the `$PTOLEMY/mk/ptbin.mk` and `$PTOLEMY/mk/stars.mk` files.

1.4.3 Combining mkPtolemyTree and pigiExample

It is possible to use the `override.mk` file used by `mkPtolemyTree` in the `pigiExample` directory to create a custom `pigiRpc` with user added stars. One reason for doing this would be to that on some platforms, stars that have been incrementally linked are not visible from the debugger. Creating a custom `pigiRpc` with the star as a built in star can aid debugging.

After running `mkPtolemyTree`, edit `$PTOLEMY/src/pigiExample/make.template` and add your stars as described in “Creating a pigiRpc that includes your own stars” on page 1-7.

1.4.4 Known Bugs in mkPtolemyTree

- To build a customized pigiRpc, you set makefile variables like `SDF` or `CG56` to 1 in your `override.mk`. If you happen to have an environment variable called `SDF` or `CG56`, this procedure fails because the rule in `stars.mk` just checks whether the variable is defined or not, not what value it has. So, ensure that you have no environment

variables that clash with the variables used in `override.mk`.

Suggested fix: In `stars.mk`, not only check whether a variable like `SDF` is defined, but also check its value.

Hopefully, the value is different from the other definition and the code is more robust.

- If `mkPtolemyTree` gives you the following message:

```
Making a customized Ptolemy development tree using the version of
Ptolemy installed in the directory /users/ptolemy
The new customized Ptolemy tree will go in /users/cxh/mypt
mkdir: illegal option -- n
mkdir: usage: mkdir [-m mode] [-p] dirname ...
```

  The try setting your path so that `/usr/ucb` is before `/usr/bin`. The problem here is that in Ptolemy 0.7, the `mkPtolemyTree` script uses the `-n` option with `echo`, which is not portable.

- `mkPtolemyTree` cannot add new directories to an already existing tree, it can only be used to create a brand new parallel tree.
- `MAKEARCH` may fail when used with a tree that was created with `mkPtolemyTree`, since `MAKEARCH` may follow symbolic links into the master tree, where the user does not have write permission.
- `mkPtolemyTree` requires that the master Ptolemy tree have a fully expanded `obj.$PTARCH` directory. Otherwise you will get an error about ‘no sources rule found’.

1.5 Using csh aliases to create a Parallel Software Development Tree

Below is a set of C shell aliases that can be used to create a parallel software development tree.

1.5.1 Aliases for Managing Symbolic Links

Below are several `csh` aliases that can be helpful when managing a duplicate hierarchy that is implemented with symbolic links:

```
alias pt 'echo $cwd | sed s:${HOME}/Ptolemy:${PTOLEMY}:'
alias ptl 'ln -s `pt`/* .'
alias sw 'mv \!^ swap$$; mv .\!^ \!^; mv swap$$ .\!^'
alias exp 'mkdir .\!^; sw \!^; cd \!^; ptl'
alias rml '\rm -f `\ls -F \!* | sed -n s/@\$//p`'
alias mkl 'rml make*; ln -s `vpath`/make* .'
```

These are documented below in detail. For convenience, these aliases can be found in the file `$PTOLEMY/.alias`.

The `pt` Alias

The `pt` alias returns the name of the “official” Ptolemy directory that corresponds to

the current directory, which is presumably in your personal hierarchy. This assumes that you have the environment variable `$PTOLEMY` set to the root directory of the "official" version of Ptolemy, and that your private version is in `~/Ptolemy`. If this is not the case, then you should make suitable modifications to definition of the `pt` alias. This alias is useful when you want to make a symbolic link to or otherwise access the "official" version of a file, as in

```
% cd ~/Ptolemy/src/domains/sdf/kernel
% ln -s `pt`/SCCS .
```

This will create a symbolic link in your directory `~/Ptolemy/src/domains/sdf/kernel` to the directory `$PTOLEMY/src/domains/sdf/kernel/SCCS`. (For information on source code control, see below).

The `ptl` Alias

The `ptl` alias uses the `pt` alias to create, in the current directory, symbolic links to all the files in the corresponding "official" directory. This is useful for quickly filling in the branches of a new directory in your private hierarchy.

```
% pwd
/users/me/Ptolemy/src/domains/ddf
% mkdir stars
% cd stars
% ptl
% ls -F
DDFCase.cc@             DDFLastOfN.cc@      DDFThresh.cc@
DDFCase.h@              DDFLastOfN.h@       DDFThresh.h@
DDFCase.pl@             DDFLastOfN.pl@      DDFThresh.pl@
DDFDownCounter.cc@      DDFRepeater.cc@     SCCS@
DDFDownCounter.h@       DDFRepeater.h@      TAGS@
DDFDownCounter.pl@      DDFRepeater.pl@     ddfstars.c@
DDFEndCase.cc@          DDFSelf.cc@         ddfstars.mk@
DDFEndCase.h@           DDFSelf.h@          make.template@
DDFEndCase.pl@          DDFSelf.pl@         makefile@
%
```

This creates a directory named `stars` and fills it with symbolic links to the contents of the corresponding directory in the "official" Ptolemy tree. Using the `-F` option of the `ls` command, makes it easy to see which files in a directory are symbolic links (they are marked with a trailing "@" sign).

The `sw` Alias

When experimenting with Ptolemy, you may want to switch back and forth between using the official version of some directory and your own version. You can keep two versions of the same directory (or a file). The `sw` alias swaps a file or directory *`filename`* with another file or directory *`.filename`*. The period at the beginning of the second file name makes it invisible unless you use the `-a` option of the `ls` command. For example, suppose you wish to experiment with making a change to just one file, `DDFRepeater.pl`, in the directory above, to fix a bug (and then send the bug fix back to the Ptolemy group):

```
% pwd
/users/me/Ptolemy/src/domains/ddf/stars
% sw DDFRepeater.pl
mv: cannot access .DDFRepeater.pl
% ls -a
./                      DDFEndCase.h@     DDFThresh.cc@
../                     DDFEndCase.pl@    DDFThresh.h@
.DDFRepeater.pl@        DDFLastOfN.cc@    DDFThresh.pl@
DDFCase.cc@             DDFLastOfN.h@     SCCS@
DDFCase.h@              DDFLastOfN.pl@    TAGS@
DDFCase.pl@             DDFRepeater.cc@   ddfstars.c@
DDFDownCounter.cc@      DDFRepeater.h@    ddfstars.mk@
DDFDownCounter.h@       DDFSelf.cc@       make.template@
DDFDownCounter.pl@      DDFSelf.h@        makefile@
DDFEndCase.cc@          DDFSelf.pl@
```

Notice that `DDFRepeater.pl` was moved to `.DDFRepeater.pl`. You can now create your own version of `DDFRepeater.pl`. To later reinstate the official version (e.g., you discovered that what you thought was a bug was in fact a feature),

```
% sw DDFRepeater.pl
```

The `exp` Alias

When starting your experimentation, the job of creating the parallel tree can be rather tedious. The `exp` aliases combines the functions of the `ptl` and `sw` aliases into one, making the common task of expanding a branch in the directory hierarchy easy. Suppose you type:

```
% exp stars
```

This is equivalent to the following sequence of commands:

```
% mkdir .stars
% sw stars
% cd stars
% ptl
```

Note that the command leaves you in the new directory ready to issue another `exp` command. For example, to create a duplicate of the directory `$PTOLEMY/src/domains/ddf/stars`, creating all subdirectories as you go, and linking to all the appropriate files in the Ptolemy tree,

```
% cd ~/Ptolemy
% exp src
% exp domains
% exp ddf
% exp stars
```

The `rml` Alias

The `rml` alias removes symbolic links in the current directory. Without an argument, it removes all the visible symbolic links. Any arguments are passed on to the `ls` command. So, to remove `all` symbolic links, including those that are invisible, use the `-a` option:

```
% rml -a
```

You can also give file names as arguments to remove just some of the symbolic links:

```
% rml *.o
```

The `mkl` alias

Suppose you wish to compile your change to the `DDFRepeater.pl` file, as above. You will need to make an object tree. Assume you are on a Sun Solaris 2.x platform. You have created a parallel tree already in `~/Ptolemy/src` (i.e. `~Ptolemy/src/domains/ddf/stars` exists). Create the corresponding object tree:

```
% cd ~Ptolemy
% exp obj.sol2
% exp domains
% exp ddf
% exp stars
% pwd
/users/me/Ptolemy/obj.sol2/domains/ddf/stars
```

The directory in which you are now located contains symbolic links to the `.o` files and makefiles in the official Ptolemy tree. If you run `make` here, your replacement `DDFRepeater.pl` star will be compiled in place of the official one. If you run "`make install`", then a library will be created and installed in the directory `~/Ptolemy/lib.sol2`, assuming this directory exists.

Running `make` as above uses the makefiles in the official Ptolemy tree, because you have symbolic links to them. Suppose you wish to modify the `make.template` file in `~/Ptolemy/src/domains/ddf/stars`. In this case, you should run the `mkl` alias to replace the `makefile` symbolic links. If you have followed the above steps, try this:

```
% pwd
/users/me/Ptolemy/obj.sol2/domains/ddf/stars
% ls -F
DDFCase.o@              DDFRepeater.o@          libddfstars.a@
DDFDownCounter.o@       DDFSelf.o@              make.template@
DDFEndCase.o@           DDFThresh.o@            makefile@
DDFLastOfN.o@           ddfstars.o@
```

(This assumes that the "official" Ptolemy has been rebuilt after being installed, otherwise the .o and .a files will be missing). Expand the makefile symbolic links:

```
% ls -l make*
```

```
lrwxrwxrwx  1 eal            56 Jul 14 11:30 make.template -> /users/
ptolemy/obj.sol2/domains/ddf/stars/make.template
lrwxrwxrwx  1 eal            51 Jul 14 11:30 makefile -> /users/
ptolemy/obj.sol2/domains/ddf/stars/makefile
```

Note that they point to the "official" makefiles. To make them point to the versions in your own tree,

```
% mkl
% ls -l make*
lrwxrwxrwx  1 eal            47 Jul 14 11:31 make.template -> ../../
../../src/domains/ddf/stars/make.template
lrwxrwxrwx  1 eal            42 Jul 14 11:31 makefile -> ../../../../
src/domains/ddf/stars/makefile
```

Now you can modify the `make.template` file in your own tree as you need.

Warning

Note that modifying Ptolemy files is risky. You will have essentially created your own version of Ptolemy. You will not be able to install future releases of Ptolemy without abandoning your version. However, if you have modifications that you believe are valuable, please communicate them to the Ptolemy group at `ptolemy@eecs.berkeley.edu`. The Ptolemy group welcomes suggestions for changes.

1.5.2 Creating a Duplicate Hierarchy

Let's look at a complete example to see how these aliases can be used. Suppose you want to modify an existing file that is part of the kernel for the SDF domain. You will need a private copy of the file that is writable. This allows you to make your changes without affecting the "official" version of Ptolemy. In order to test your change, you will have to build a private version of the interpreter `ptcl` or the graphical interface `pigiRpc`.

First, create the root directory for your duplicate hierarchy.

```
% mkdir ~/Ptolemy
```

Then go into that directory and create symbolic links to all files in the corresponding "official" Ptolemy directory.

```
% cd ~/Ptolemy
% ptl
```

You will want to have a private version of the `lib.$PTARCH` directory so that you won't modify the "official" version of any library or object files.

```
% cd ~/Ptolemy
% exp lib.$PTARCH
```

(This assumes your `$PTARCH` environment variable is set). You will also want a private

`obj.$PTARCH` directory for the same reason. In this example, the tree is expanded down to the `sdf` directory:

```
% cd ~/Ptolemy
% exp obj.$PTARCH
% exp domains
% exp sdf
```

If you are modifying code in the `sdf/kernel` directory, then you will want to expand it as well. Once expanded, you will want remove the `make.template` and `makefile` links (which point to the "official" Ptolemy files) and replace them with links that use relative paths to refer to your private versions of these files (in case you make changes to them):

```
% exp kernel
% mkl
```

If you make changes in the `sdf/kernel` directory, then there is a good chance that object files in `sdf/dsp` and other directories will also have to be recompiled. Thus, you will want to expand these directories (and any subdirectories below them) as well. Remember to replace the `make.template` and `makefile` links as in the `sdf/kernel` directory.

```
% exp dsp
% mkl
% exp stars
% mkl
```

Because of the way symbolic links work, it is important to remove the links for the `.o` and `.a` files in the directories you have just created. You can do this by issuing a `make realclean` command in the `obj.$PTARCH/domains/sdf` directory. This will recursively clean out all the subdirectories. You could also do this manually by issuing a `rml *.o *.a` command in each directory.

You will also need a private version of the `src` directory.

```
% cd ~/Ptolemy
% exp src
% exp domains
% exp sdf
% exp kernel
```

At any point after this, it is possible to switch back and forth between private and "official" versions of these directories with the `sw` alias. In fact, you just used it (as part of the `exp` alias) to switch to the private versions of the `obj.$PTARCH`, `lib.$PTARCH`, and `src` directories.

To compile your version of the sdf kernel directory,

```
% cd ~/Ptolemy/obj.$PTARCH/domains/sdf/kernel
% make install
```

To make a version pigiRpc (or better yet, ptinyRpc) with your changes,

```
% cd ~/Ptolemy/obj.$PTARCH
% exp pigiRpc
% mkl
% make ptinyRpc
```

1.5.3 Source Code Control

At the present time, at Berkeley, the Ptolemy group uses SCCS for source code control. This means that each directory with source code in it contains a subdirectory called SCCS. That subdirectory is not distributed with Ptolemy, but if you are starting your own development expanding on Ptolemy, you may wish to use a similar mechanism. We assume here that you are familiar with SCCS, which is a standard Unix facility.

Recall the command above:

```
% pwd
/users/me/Ptolemy/src/domains/ddf/stars
% sw DDFRepeater.pl
mv: cannot access .DDFRepeater.pl
% ls -a
./                      DDFEndCase.h@       DDFThresh.cc@
../                     DDFEndCase.pl@      DDFThresh.h@
.DDFRepeater.pl@        DDFLastOfN.cc@      DDFThresh.pl@
DDFCase.cc@             DDFLastOfN.h@       SCCS@
DDFCase.h@              DDFLastOfN.pl@      TAGS@
DDFCase.pl@             DDFRepeater.cc@     ddfstars.c@
DDFDownCounter.cc@      DDFRepeater.h@      ddfstars.mk@
DDFDownCounter.h@       DDFSelf.cc@         make.template@
DDFDownCounter.pl@      DDFSelf.h@          makefile@
DDFEndCase.cc@          DDFSelf.pl@
```

Note the symbolic link to the “official” SCCS directory. This will not be present if you are using the distributed Ptolemy and have not created it. Assume, however, that you have put this directory under SCCS control (or someone else has). Then you can create an editable version of the `DDFRepeater.pl` star with the command:

```
% sccs edit DDFRepeater.pl
1.24
new delta 1.25
76 lines
```

The sccs utility tells you the latest version number (1.24) and assigns you a new version number (1.25). You can now edit the file safely (nobody else will be allowed by sccs to edit it). When you are done and have fully tested your changes (and obtained clearance from the Ptolemy group if necessary), you can check the file back in:

```
% sccs delget DDFRepeater.pl
comments?
```

You should enter an explanation of your changes. If you wish to nullify your changes, restor-

ing the official version,

```
% sccs unedit DDFRepeater.pl
```

and if you wish to create a new file and put it under SCCS control,

```
% sccs create -fi NewFileName
```

1.6 Building standalone programs that use Ptolemy libraries.

Sometimes it is necessary to create small standalone programs that use part of the Ptolemy libraries.

Examples of this are the desire to use Ptolemy kernel classes such as `StringList` or the need to isolate an obscure bug or memory leak. The `$PTOLEMY/mk/standalone.mk` file provides the make definitions to make this possible. This file provides make rule definitions to build various binaries some using the Pure Sofware Inc.[1] utilities.

The usage for this makefile is:

`make -f $PTOLEMY/mk/standalone.mk` *`stars.mk_variable_defs filename.suffix`*

Where *`stars.mk_variable_defs`* is zero or more makefile variables used in `$PTOLEMY/mk/stars.mk`, such as `SDF=1`. *`filename`* is the base name of the file to be compiled, and the basename of the output file. and *`suffix`* is one of the forms listed in table 1-1.

Suffix	Binary Type
`.bin`	Standard binary
`.debug`	Binary with debug symbols
`.purify`	Binary with Purify and debug symbols
`.quantify`	Binary with Quantify linked in
`.purecov`	Binary with Pure Coverage linked in

TABLE 1-1: Table of filename suffixes and binary types.

It is possible to use these makefiles to create binaries that do not have any Ptolemy code. A reason why you might want to do this is to take advantage of the Pure Software make definitions in `standalone.mk`. To specify no Ptolemy libraries, use the make argument `NOPTOLEMY=1`.

1.6.1 Standalone example using StringList

For example, say you want to use the `StringList` class in a standalone program

1. Rational (http://www.rational.com) sells tools such as:
   Purify, which can be used to find memory leaks and out of bounds memory accesses.
   Quantify, which can be used to profile performance.
   Purecov, which can be used to provide code coverage information.

named `bar.cc`:

```
#include
#include "StringList.h"
main() {
      StringList testing = "This is a test\n";
      cout << testing;
}
```

To build it you would type:

```
make -f $PTOLEMY/mk/standalone.mk bar.bin
```

If you wanted to make a new standalone program that also uses part of the CG domain, just define the domain make variables (as used in stars.mk) on the make command line:

```
make -f $PTOLEMY/mk/standalone.mk CG=1 bar.bin
```

If you are going to do this often, it may be useful to create a new directory in which to test this program. In this directory, execute the commands:

```
ln -s $PTOLEMY/mk/standalone.mk makefile
ln -s $PTOLEMY/mk/standalone.mk make.template
```

By having these symbolic links, you will not have to supply the make argument `-f $PTOLEMY/mk/standalone.mk` as before.

1.6.2 Standalone example that tests a Scheduler

Here is an example of a minimal file that can be used to call the setup in a Scheduler for instance. If the file `testAcyLoopSched.cc` contains:

```
#include <iostream.h>
#include "Galaxy.h"
#include "SDFStar.h"
#include "AcyCluster.h"
#include "AcyLoopScheduler.h"
#include "SDFPortHole.h"

main() {
      // First create a simple galaxy and some stars.
      SDFStar star[3];
      Galaxy topGalaxy;
      topGalaxy.setDomain("SDF");
      topGalaxy.setName("topGalaxy");
      topGalaxy.addBlock(star[0],"star0");
      topGalaxy.addBlock(star[1],"star1");
      topGalaxy.addBlock(star[2],"star2");

      // Add ports to stars.
      OutSDFPort p0,p1;
      InSDFPort p2,p3;

      // initialize the ports
      p0.setPort("output1",&star[0],FLOAT,2);
      star[0].addPort(p0);
      p1.setPort("output2",&star[0],FLOAT,3);
      star[0].addPort(p1);
      p2.setPort("input",&star[1],FLOAT,3);
```

```
        p3.setPort("input",&star[2],FLOAT,2);
        star[1].addPort(p2);
        star[2].addPort(p3);

        // Connect 'em up.  The graph is
        // star[1] (3) <--- (2) star[0] (3) ---> (2) star[2]
        p0.connect(p2,0);
        p1.connect(p3,0);

        // Scheduling
        AcyLoopScheduler sched;
        sched.setGalaxy(topGalaxy);
        cout << "No problem till now.  Calling sched.setup()...\n";
        sched.setup();
        int i;
        for (i = 0 ; i < 3 ; i++) {
              cout << star[i].fullName() << "\n";
              cout << "Repetitions = " << star[i].reps() << "\n";
        }
        StringList sch = sched.displaySchedule();
        cout << sch;
}
```

The command to compile this and produce a standalone binary would be:

```
make -f $PTOLEMY/mk/standalone.mk OPTIMIZER= SDF=1 \
      USE_SHARED_LIBS=yes testAcyLoopSched.debug
```

1.7 Debugging Ptolemy and Extensions Within Pigi

The extensibility of Ptolemy can introduce problems. Code that you add may be defective (few people write perfect code every time), or may interact with Ptolemy in unexpected ways. These problems most frequently manifest themselves as a Ptolemy crash, where the Ptolemy kernel aborts, creating a core file.

The fact that `pigiRpc` and `vem` are separate Unix processes has the advantage that when `pigiRpc` aborts with a fatal error, `vem` keeps running. Your `vem` schematic is unharmed and can be safely saved. Vem gives a cryptic error message something like:

```
RPC Error: server: application exited without calling
RPCExit
Closing Application /home/ohm1/users/messer/ptolemy/lib/
pigiRpcShell on host foucault.berkeley.edu
Elapsed time is 1538 seconds
```

The message

```
segmentation fault (core dumped)
```

may appear in the window from which you started `pigi`. The first line in the above message might alternatively read

```
RPC Error: fread of long failed
```

Vem is trying to tell you that it is unable to get data from the link to the Ptolemy kernel. In either case, it will create a large file in your home directory called `core`. The `core`[1] file is

useful for finding the problem.

1.7.1 A quick scan of the stack

Assuming you are using Gnu tools, and assuming the `pigiRpc` executable that you are using is in your path, go to your home directory and type:

```
gdb pigiRpc
```

The Gnu symbolic debugger (`gdb`) will show the state of the stack at the point where the program failed. Note that `gdb` is not distributed with Ptolemy, but is available free over the Internet in many places, including `ftp://prep.ai.mit.edu/pub/gnu`. The most recently called function might give you a clue about the cause of the problem. Here is a typical session:

```
cxh@watson 197% gdb pigiRpc ~/core
GDB is free software and you are welcome to distribute copies of it
under certain conditions; type “show copying” to see the conditions.
There is absolutely no warranty for GDB; type “show warranty” for
details.
GDB 4.15.1 (sparc-sun-solaris2.4),
Copyright 1995 Free Software Foundation, Inc...
(no debugging symbols found)...
```

Tell `gdb` to read in the core file.

```
(gdb) core core
Core was generated by `/users/ptolemy/bin.sol2/pigiRpc :0.0 wat-
son.eecs.berkeley.edu 32870 inet 1 2 3’.
Program terminated with signal 11, Segmentation fault.
Reading symbols from
            /users/ptolemy/lib.sol2/libcg56dspstars.so...done.
Reading symbols from
            /users/ptolemy/lib.sol2/libcg56stars.so...done.
```

Since this version of Ptolemy uses shared libraries, we see lots of messages about shared libraries, which we’ve deleted here for brevity.

```
(gdb) where
#0  0xee7a1c20 in _kill ()
#1  0x52b04 in pthread_clear_sighandler ()
#2  0x52cb4 in pthread_clear_sighandler ()
#3  0x53130 in pthread_clear_sighandler ()
#4  0x53320 in pthread_handle_one_process_signal ()
#5  0x55658 in pthread_signal_sched ()
#6  0x554d8 in called_from_sighandler ()
#7  0x535e4 in pthread_handle_pending_signals ()
#8  0x10100c in SimControl::getPollFlag ()
#9  0x101604 in Star::run ()
#10 0xd394c in DataFlowStar::run ()
#11 0xeeca5fb8 in SDFAtomCluster::run (this=0x2bd0b0)
at ../../../../src/domains/sdf/kernel/SDFCluster.cc:1032
#12 0xeeca0f20 in SDFScheduler::runOnce (this=0x2bd050)
at ../../../../src/domains/sdf/kernel/SDFScheduler.cc:121
#13 0xeeca0eac in SDFScheduler::run (this=0x2bd050)
at ../../../../src/domains/sdf/kernel/SDFScheduler.cc:98
```

1. Note that core files can be large in size, so your system administrator may have setup the csh “limit” command to disable the creation of core files. For further information, see the csh man page.

```
#14 0x108358 in Target::run ()
#15 0x109e04 in Runnable::run ()
#16 0xe62ec in InterpUniverse::run ()
#17 0xee9e7f04 in PTcl::run (this=0x20af80, argc=2949528,
argv=0x109fa4)
at ../../src/ptcl/PTcl.cc:521
#18 0xee9e99a4 in PTcl::dispatcher (which=0x27, interp=0x1d4830,
argc=2,
```

The "where" command shows that state of the stack at the time of the crash. The actual stack trace was 72 frames long, the last two frames being:

```
#71 0xeec06d5c in ptkMainLoop ()
     at ../../src/pigilib/ptkTkSetup.c:192
#72 0x4982c in main ()
```

Scanning this list we can recognize that the crash occurred during the execution of a star. Unfortunately, unless you are running a version of `pigiRpc` with the debug symbols loaded, it will be difficult to tell much more from this.

1.7.2 More extensive debugging

To do more extensive debugging, you need to create or find a version of `pigiRpc` with debug symbols, called `pigiRpc.debug`.

The first step is to build a `pigiRpc` that contains the domains you are interested in debugging. There are several ways to build a `pigiRpc`:

a. There may be prebuilt debug binaries on the Ptolemy Web site, check the directory that contains the latest release.

b. Rebuild the entire tree from scratch. This takes about 3 hours. Appendix A in the Ptolemy User's Manual has instructions about this.

c. Use `mkPtolemyTree` to rebuild a subset of the Ptolemy tree. See "Using mkPtolemyTree to create a custom Ptolemy trees" on page 1-9 for more information.

d. Use the csh aliases to rebuild a subset of the Ptolemy tree. See "Using csh aliases to create a Parallel Software Development Tree" on page 1-12 for more information.

The next step is to build the `pigiRpc.debug` binary:

```
cd $PTOLEMY/obj.$PTARCH/pigiRpc; make pigiRpc.debug
```

Then set the `PIGIRPC` environment variable to point to the binary:

```
setenv PIGIRPC $PTOLEMY/obj.$PTARCH/pigiRpc/pigiRpc.debug[1]
```

Then run pigi as follows:

```
pigi -debug
```

An extra window running `gdb` appears. (If this fails, then `gdb` is probably not installed at your

1. Note that the pigi script will attempt to find pigiRpc.debug binary if the PIGIRPC environment variable is not set. An alternative is that one can avoid setting PIGIRPC and use the pigi -rpc option to specify a binary.The command would be:
pigi -debug -rpc $PTOLEMY/obj.$PTARCH/pigiRpc/pigiRpc.debug

site or is not in your path.) Type `cont` to continue past the initial breakpoint.

Now, if you can replicate the situation that created the crash, you will be able to get more information about what happened. Here is a sample of interaction with the debugger through the `gdb` window:

```
GDB is free software and you are welcome to distribute copies of it
under certain conditions; type “show copying” to see the conditions.
There is absolutely no warranty for GDB; type “show warranty” for
details.
GDB 4.15.1 (sparc-sun-solaris2.4),
Copyright 1995 Free Software Foundation, Inc...
Breakpoint 1 at 0x39ab4: file ../../src/pigiExample/pigiMain.cc, line
58.
Breakpoint 1, main (argc=-282850408, argv=0x399c0)
at ../../src/pigiExample/pigiMain.cc:58
58              pigiFilename = argv[0];
(gdb) cont
Continuing.
```

At this point, you are running Ptolemy. Use it in the usual way to replicate your problem. When you succeed, you will get a message something like:

```
Program received signal SIGSEGV, Segmentation fault.
0xeee81394 in mxRealMax ()
(gdb)
```

At this point you can again examine the stack. This time, however, there will be more information. Here, we examine the top 5 frames of the stack

```
(gdb) where 5
#0  0xeee81394 in mxRealMax ()
#1  0xe3864 in SimControl::getPollFlag () at ../../src/kernel/SimCon-
trol.cc:271
#2  0xe3e5c in Star::run (this=0x28c908) at ../../src/kernel/
Star.cc:73
#3  0xbacb8 in DataFlowStar::run (this=0x28c908)
at ../../src/kernel/DataFlowStar.cc:94
#4  0xef485fb8 in SDFAtomCluster::run (this=0x278570)
at ../../../../src/domains/sdf/kernel/SDFCluster.cc:1032
(More stack frames follow...)
(gdb)
```

This particular stack trace is a little strange at the “bottom” (gdb calls the lower numbers the bottom even though they are at the top of the list) because it was generated by invoking a dynamically linked star, and the symbol information is not complete. However, you can still find out quite a bit. Notice that you are now told where the files are that define the methods being called. The file names are all relative to the directory in which the corresponding object file normally resides. The Ptolemy files can all be found in some subdirectory of `$PTOLEMY/src`.

You can get help from `gdb` by typing “help”. Suppose you wish to find out first which star is being run when the crash occurs. The following sequence moves up in the stack until the “run” call of a star:

```
(gdb) up
#1  0xe3864 in SimControl::getPollFlag () at ../../src/kernel/SimCon-
trol.cc:271
```

```
271             ptBlockSig(SIGALRM);
(gdb) up
#2  0xe3e5c in Star::run (this=0x28c908) at ../../src/kernel/
Star.cc:73
73              go();
(gdb)
```

At this point, you can see that line 73 of the file `$PTOLEMY/src/kernel/Star.cc` reads

```
go();
```

Odds are pretty good that the problem is in the `go()` method of the star. You can find out to which star this method belongs as follows:

```
(gdb) p *this
$1 = {<Block> = {<NamedObj> = {nm = 0x28ad58 "BadStar1",
      prnt = 0x28c878,
      myDescriptor = 0x28b658 "Causes a core dump deliberately",
      _vptr. = 0xeee91738}, flags = {nElements = 0, val = 0x0},
      pTarget = 0x28aa60, scp = 0x0,
ports = {<NamedObjList> = {<SequentialList> =
      {lastNode = 0x0, dimen = 0}, }, }, states = {<NamedObjList> =
      {<SequentialList> = { lastNode = 0x0, dimen = 0}, }, },
multiports = {<NamedObjList> = {<SequentialList> =
      {lastNode = 0x0, dimen = 0}, }, }},
      indexValue = -1, inStateFlag = 1}
(gdb)
```

This tells you that a star with name (`nm`) `BadStar1` and descriptor “Causes a core dump deliberately.” is being invoked. This particular star has the following erroneous go method:

```
go {
      char* p = 0;
      *p = 'c';
}
```

More elaborate debugging requires that the symbols for the star be included. The easiest way to do this is to build a version of `pigiRpc.debug` that includes your star already linked into the system. Then repeat the above procedure. The bottom of the stack frame will have much more complete information about what is occurring.

1.7.3 Debugging hints

Below are some hints for debugging.

• “Miscellaneous debugging hints for gdb” on page 1-28

See also Appendix A of the Ptolemy User’s manual.

Using emacs, gdb and pigi

By default, `gdb` is started in an X terminal window with its default command line interface. Many people prefer to interface with `gdb` through `emacs`, which provides much more sophisticated interaction between the source code and the debugger. To get an `emacs` interface to `gdb` (assuming `emacs` is installed on your system), set the following environment variable:

```
setenv PT_DEBUG ptgdb
```

To find out more about using `gdb` from within `emacs`, start up `emacs` and type:

```
M-x info
Then type:
m emacs
```

Then go down to:

```
Running Debuggers Under Emacs

* Starting GUD::        How to start a debugger subprocess.
* Debugger Operation::  Connection between the \
debugger and source buffers.
* Commands of GUD::     Key bindings for common commands.
* GUD Customization::   Defining your own commands for GUD.
```

Gdb and the environment

Note that the documentation for `gdb` says the following:

```
*Warning:* GDB runs your program using the shell indicated by your
`SHELL' environment variable if it exists (or `/bin/sh' if not). If
your `SHELL' variable names a shell that runs an initialization file-
-such as `.cshrc' for C-shell, or `.bashrc' for BASH--any variables
you set in that file affect your program. You may wish to move setting
of environment variables to files that are only run when you sign on,
such as `.login' or `.profile'.
```

Optimization

By default, Ptolemy is compiled with the optimizer turn up to a very high level. This can result in strange behavior inside the debugger, as the compiler may evaluate instructions in a different order than they appear in the source file. You may find it easier to debug a file by recompiling it with the optimization turned off by removing the corresponding `.o` file and doing:

```
make OPTIMIZER= install
```

Debugging StringLists in gdb

Ptolemy uses `StringList` object to manipulate strings. However, using `gdb` to view

a StringList object can be non-intuitive. To print the contents of a Stringlist *myStringList* as one item per line from within gdb, use:

```
p displayStringListItems(myStringList)
```

To print out the StringList as a contiguous string, use:

```
p displayStringList(myStringList)
```

How to use ptcl to speed up the compile/test cycle.

If you are spending a lot of time debugging a problem, you may want to use ptcl instead of pigiRpc, as ptcl is smaller and starts up faster. Also, you can keep your breakpoints between invocations of ptcl, as debugging ptcl does not start up a separate emacs each time. However, ptcl cannot handle demos that use Tk.

Here's how to use ptcl to debug.

1. Run pigiRpc on the universe, and use compile-facet to generate a ~/pigiLog.pt file. Note the number of iterations for the universe, and then exit pigiRpc.
2. Copy ~/pigiLog.pt to somewhere. A short file name, like /tmp/tst.tcl will save time in typing since you may be typing it often. Don't use something inside your home directory as you can't easily use ~ inside ptcl.
3. Edit the file and add a run *XXX* line and a wrapup line at the end. If the demo should run for 100 iterations, then add:

   ```
   run 100
   wrapup
   ```

   to the end of the file.
4. Build a ptcl.debug that has just exactly the functionality you need by using an override.mk file. Alternatively, you could use either ptcl.ptrim.debug or ptcl.ptiny.debug. If your demo is SDF, then try building and using ptcl.ptiny.debug.
5. If you use emacs, then you can start up gdb on your binary with:

   ```
   M-x gdb
   ```
6. Then type in the name of the binary. You may have to use the full pathname.
7. Inside emacs, you can then set breakpoints in the gdb window, either by typing a break command, or by viewing the file and typing Control-X space at the location you would like a break point.
8. Type r to start the process, and then source your demo with:

   ```
   source /tmp/tst.tcl
   ```

   If you want to recompile your demo outside of gdb and then reload it into your gdb session, use the file command inside gdb:

```
file /users/cxh/pt/obj.sol2/ptcl/ptcl.ptiny.debug
```

Your breakpoints will be saved, which is a big time saver.

Miscellaneous debugging hints for gdb

If you are having problems debugging with `gdb`, here's what to check.

1. Verify that your `$PTOLEMY` is set to what you intended. If you are building binaries in your private tree, be sure that `$PTOLEMY` is set to your private tree and not `~ptdesign` or `/users/ptolemy`.
2. Verify that your `$LD_LIBRARY_PATH` does not include libraries in another Ptolemy tree. You could type:

   ```
   unsetenv $LD_LIBRARY_PATH
   ```

3. `gdb` sources your `.cshrc`, so your `$PTOLEMY` and `$LD_LIBRARY_PATH` could be different. Inside `gdb`, use

   ```
   show env PTOLEMY
   ```

   to see what it is set to. This problem is especially common if you are running `gdb` inside `emacs` via `ptgdb`.
4. Verify that you are running the right binary by looking at the creation times. You may find it useful to use the `-rpc` option:

```
pigi -debug -rpc $PTOLEMY/obj.$PTARCH/pigiRpc/pigiRpc.mine ~ptdesign/
init.pal
```

5. Recompile the problem files with optimization turned off and relink your `pigiRpc`. You can do this with

```
rm myfile.o; make OPTIMIZER= install
```

   Then rebuild your `pigiRpc`

6. Look for weird coding styles that could confuse the line count in emacs and gdb, such as declaring variables in the middle of a block and brackets that open a function body on the same line as the function declaration:

```
int foo(int bar){
```

   vs.

```
int foo(int bar)
            {
```

7. Use `stepi` to step by instructions, rather than `step`.

Chapter 2. Writing Stars for Simulation

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2.1 Introduction

Ptolemy provides rich libraries of stars for the more mature domains. Since the stars were designed to be as generic as possible, many complicated functions can be realized by a galaxy. Nonetheless, no star library can possibly be complete; you may need to design your own stars. The Ptolemy preprocessor language makes this easier than it could be. This chapter is devoted to the use of the preprocessor language.

Newly designed stars can be dynamically linked into Ptolemy, avoiding frequent recompilation of the system. If the new stars are generic and useful, however, it might be better to add them to the list of compiled-in stars and rebuild the system. See "Creating Custom Versions of pigiRpc" on page 1-6.

2.2 Adding stars dynamically to Ptolemy

To get a quick sense of what it means to create a new star, you can use one of the existing stars as a template. Create a new directory in which you have write permission. Copy the source code for an existing Ptolemy star. For example,

```
cd my_directory
cp $PTOLEMY/src/domains/sdf/stars/SDFSin.pl SDFMyStar.pl
chmod +w SDFMyStar.pl
```

The "`.pl`" extensions on the file names stand for "Ptolemy language" or "preprocessor language." The file name must be of the form *`DomainStarname`*`.pl` for dynamic linking and the `look-inside` command to work. The last command just ensures that you can modify the file. Edit the file to change the name of the star from `Sin` to `MyStar`. This is necessary so that the name does not conflict with the existing `Sin` star in the SDF domain.

You can now dynamically link your new star. Start `pigi`, the graphical editor. If you start `pigi` in your new directory, you will get a blank `init.pal` facet. Place your mouse cursor in this facet, and issue the "make-star" command (the shortcut is "`*`"). A dialog box like

the following will appear:

Enter the name of the star, `MyStar`, its domain, `SDF`, the location of the directory that defines it, such as `~user_name/my_directory`, and the name of palette in which you would like its icon to appear, `user.pal`. The star will be compiled and dynamically linked with the Ptolemy executable. An icon for it will appear in the facet `user.pal`. Try using this in a simple system.

Three details about dynamic linking may prove useful:

- If the name of the star source directory has a `/src/` component, `pigi` will replace this with `/obj.$PTARCH/` depending on the type of machine you are running, to get the name of the directory in which to store the object file. This is especially useful if you are jointly doing development with others who use a different type of machine. If there is no `/src/` component in the name, then the object file is placed in the same directory with the source file.
- If there is a file named `Makefile` or `makefile` in the object file directory, `pigi` will run the `make` program, using the `makefile` to create the object file (or make sure it is up to date). If there is no `makefile`, `pigi` will run a make-like procedure on its own, running the preprocessor as needed to produce the C++ source files, then running the C++ compiler to create the object file. By default, the C++ compiler will be told to look for include files in the kernel directory and the domain-specific kernel and star directories; if this is not adequate, then you need to write a makefile. Once compilation (if any) is complete, the dynamic linker is used to load the star into the system. Compilation errors, if any, will appear in a popup window.
- Whenever the definition of a star is changed so that the new definition has different I/O ports, the icon must be updated as well. You can do this by calling *makestar* again to replace the old icon with a new one.

If the linking fails, one of the following situations may apply:

- Whoever installed Ptolemy did not install the compiler.
- The compiler is not configured correctly. If you are using a prebuilt compiler obtained from the Ptolemy ftp site, you may need to set some environment variables if your Ptolemy installation is not at `/users/ptolemy`. See Appendix A of the Ptolemy *User's Manual* for more information.
- A spurious `makefile` exists in your directory. If a `makefile` exists in your directory, Ptolemy will attempt to use it to compile your star. Remove it, and try again.

- The version of the compiler used to build Ptolemy is not the same as the version used to compile your star. This should not occur if you are using the compiler distributed with Ptolemy, but can occur if the compiler has been updated since Ptolemy was last built, or if you are not using the compiler distributed with Ptolemy.
- You have a `/src/` component in the directory name, but the corresponding `/obj.$PTARCH/` directory does not exist or cannot be written. A common error is to put the Ptolemy sources in `/usr/local/src/ptolemy`, which confuses Ptolemy since a star might be in `/usr/local/src/ptolemy/src/domains/sdf/stars`, which has two `/src/` directories in the path.

You may find it helpful to refer to the Appendix A, Installation and Troubleshooting in the *User's Manual*.

The star you just created performs exactly the same function as an existing star in the Ptolemy library, and hence is not very interesting. Try modifying the star. For example, you could add 1.0 to the sine before producing the output. Find the definition of the `go` method, which should look like this:

```
go {
      output%0 << sin (double(input%0));
}
```

The one line of code is ordinary C++ code, although the "`<<`" and "`%`" operators have been overloaded. This line means that the current value (`%0`) of the output named "`output`" should be assigned the value returned by the `sin` function applied to the current value of the input named "`input`". The cast to `double` indicates that we are not really interested in the `Particle` object supplied by the input, but rather its value, interpreted as a double-precision floating point number. Try changing this code to

```
go {
      output%0 << sin (double(input%0)) + 1.0;
}
```

To recompile and reload the star, place your mouse cursor on any instance of the icon for the star, and type "`L`" (or invoke the "Extend:load-star" command through the menus).

Sometimes, you will wish to dynamically link stars that are derived from other stars that you have dynamically linked. To do this, the base class stars must be *permanently linked*. This can be done with the "Extend:load-star-perm" command ("`K`"). To do this, place the mouse over an icon representing the parent star, and type "`K`". Once the parent star is permanently linked, it cannot be replaced or redefined: you must restart `pigi`.

The `go` and all other entries in the `.pl` file defining the star are explained in the following sections.

2.3 The Ptolemy preprocessor language (ptlang)

The Ptolemy preprocessor, `ptlang`, was created to make it easier to write and document star class definitions to run under Ptolemy. Instead of writing all the class definitions and initialization code required for a Ptolemy star, the user can concentrate on writing the action code for a star and let the preprocessor generate the standard initialization code for portholes, states, etc. The preprocessor generates standard C++ code, divided into two files (a header file

with a `.h` extension and an implementation file with a `.cc` extension). It also generates standardized documentation, in a file with a `.html` extension, to be included in the manual. In releases before Ptolemy 0.7, Ptolemy used `.t` files, which conained troff source

2.3.1 Invoking the preprocessor

The definition of a star named YYY in domain XXX should appear in file with the name `XXXYYY.pl`. The class that implements this star will be named XXXYYY. Then, running the command

```
ptlang XXXYYY.pl
```

will produce the files `XXXYYY.cc`, `XXXYYY.h`, and `XXXYYY.html`. Implementation of the preprocessor

The preprocessor is written in `yacc` and C. It does not attempt to parse the parts of the language that consist of C++ code (for example, `go` methods); for these, it simply counts curly braces to find the ends of the items in question. It outputs `#line` directives so the C++ compiler will print error messages, if any, with respect to the original source file.

2.3.2 An example

To make things clearer, let us start with an example, a rectangular pulse star in the file `SDFRect.pl`:

```
defstar {
      name { Rect }
      domain { SDF }
      desc {
Generates a rectangular pulse of height "height" (default 1.0).
with width "width" (default 8).
      }
      version {%W% %G%}
      author { J. T. Buck }
      copyright {1993 The Regents of the University of California}
      location { SDF main library }
      state {
            name { height }
            type { float }
            default { 1.0 }
            desc { Height of the rectangular pulse. }
      }
      state {
            name { width }
            type { int }
            default { 8 }
            desc { Width of the rectangular pulse. }
      }
      state {
            name { count }
            type { int }
            default { 0 }
            desc { Internal counting state. }
            attributes { A_NONSETTABLE|A_NONCONSTANT }
```

```
        }
        output {    // the output port
              name { output }
              type { float }
              desc { The output pulse. }
        }
        go {              // the run-time function
              double t = 0.0;
              if (count < width) t = height;
              count = int(count) + 1;
              output%0 << t;
        }
}
```

Running the preprocessor on the above file produces the three files `SDFRect.h`, `SDFRect.cc` and `SDFRect.html`; the names are determined *not* by the input filename but by concatenating the domain and name fields. These files define a class named `SDFRect`.

At the time of this writing, only one type of declaration may appear at the top level of a Ptolemy language file, a `defstar`, used to define a star. Sometime in the future, a `defgalaxy` section may also be supported. The `defstar` section is itself composed of subitems that define various attributes of the star. All subitems are of the form

keyword { *body* }

where the *body* may itself be composed of sub-subitems, or may be C++ code (in which case the Ptolemy language preprocessor checks it only for balanced curly braces). Note that the keywords are *not* reserved words; they may also be used as identifiers in the body.

2.3.3 Items that appear in a defstar

The following items can appear in a `defstar` directive. The items are given in the order in which they typically appear in a star definition (although they can appear in any order). An alphabetical listing and summary of directives is given in table 2-1.

name

This is a required item, and has the syntax

name { *identifier* }

It (together with the domain) provides the name of the class to be defined and the names of the output files. Case is important in the identifier.

domain

This is a required item; it specifies the domain, such as SDF. The syntax is:

domain { *identifier* }

where *identifier* specifies the domain (again, case is important).

keyword	summary	required	page
acknowledge	the names of other contributors to the star	no	2-8
author	the name(s) of the author(s)	no	2-8
begin	C++ code to execute at start time, *after* the scheduler setup method is called	no	2-13
ccinclude	specify other files to include in the .cc file	no	2-15
code	C++ code to include in the .cc file outside the class definition	no	2-15
codeblock	define a code segment for a code-generation star	no	13-2
conscalls	define constructor calls for members of the star class	no	2-13
constructor	C++ code to include in the constructor for the star	no	2-12
copyright	copyright information to include in the generated code	no	2-8
derived	alternative form of derivedFrom	no	2-7
derivedfrom	the base class, which must also be a star	no	2-7
desc	alternative form of descriptor	no	2-7
descriptor	a short summary of the functionality of the star	no	2-7
destructor	C++ code to include in the destructor for the star	no	2-13
domain	the domain, and the prefix of the name of the class	yes	2-5
explanation	full documentation (See also htmldoc).	no	2-9
exectime	specify the execution time for a code generation star	no	13-2
go	C++ code to execute when the star fires	no	2-14
header	C++ code to include in the .h file, before the class definition	no	2-15
hinclude	specify other files to include in the .h file	no	2-15
htmldoc	full documentation, optionally using HTML directives		
inmulti	define a set of inputs	no	2-11
inout	define a (bidirectional) input and output	no	2-11
inoutmulti	define a set of (bidirectional) inputs and outputs	no	2-11
input	define an input to the star	no	2-11
location	an indication of where a user might find the star	no	2-8
method	define a member function for the star class	no	2-15
name	the name of the star, and the root of the name of the class	yes	2-5
outmulti	define a set of outputs	no	2-11
output	define an output from the star	no	2-11
private	define private data members of the star class	no	2-14
protected	defined protected data members of the star class	no	2-14
public	define public data members of the star class	no	2-14
setup	C++ code to execute at start time, *before* compile-time scheduling	no	2-13
state	define a state or parameter	no	2-9
version	version number and date	no	2-7

TABLE 2-1: A summary of the items used to define a star. Additional items are allowed in code generation stars, as explained in later chapters. A minimal set of the most useful items are shaded.

derivedfrom

This optional item indicates that the star is derived from another class. Syntax:

```
derivedfrom { identifier }
```

where *identifier* specifies the base class. The `.h` file for the base class is automatically included in the output `.h` file, assuming it can be located (you may need to create a makefile).

For example, the `LMS` star in the `SDF` domain is derived from the `FIR` star. The full name of the base class is `SDFFIR`, but the `derivedfrom` statement allows you to say either

```
derivedfrom { FIR }
```

or

```
derivedfrom { SDFFIR }
```

The `derivedfrom` statement may also be written `derivedFrom` or `derived`.

descriptor

This item defines a short description of the class. This description is displayed by the `profile` pigi command. It has the syntax

```
descriptor { text }
```

where *text* is simply a section of text that will become the short descriptor of the star. You may also write `desc` instead of `descriptor`. A principal use of the short descriptor is to get on-screen help, so the descriptor should not include any troff formatting commands. Unlike the `htmldoc` (described below), it does not pass through troff. The following are legal descriptors:

```
desc { A one line descriptor. }
```

or

```
desc {
A multi-line descriptor. The same line breaks and spacing
will be used when the descriptor is displayed on the screen.
}
```

By convention, in these descriptors, references to the names of states, inputs, and outputs should be enclosed in quotation marks. Also, each descriptor should begin with a capital letter, and end with a period. If the descriptor seems to get long, augment it with the `htmldoc` directive, explained below. However, it should be long enough so that it is sufficient to explain the function of the star.

version

This item contains two entries as shown below

```
version { number MO/DA/YR }
```

where the *number* is a version number, and the *MO/DA/YR* is the version date. If you are using SCCS for version control then the following syntax will work well:

```
version { %W% %G% }
```

When the file is checked in by SCCS, the string `%W%` will be replaced with a string of the form: `@(#)filename num`, where num is the version number, and `%G%` will be replaced with a properly formatted date.

author

This optional entry identifies the author or authors of the star. The syntax is

```
author { author1, author2 and author3 }
```

Any set of characters between the braces will be interpreted as a list of author names.

acknowledge

This optional entry attaches an acknowledgment section to the documentation. The syntax is

```
acknowledge { arbitrary single line of text }
```

copyright

This optional entry attaches a copyright notice to the `.h`, `.cc`, and `.t` files. The syntax is

```
copyright { copyright information }
```

For example, we used to use the following (our lawyers have recently caused us to increase the verbosity):

```
copyright {1994 The Regents of the University of California}
```

The copyright may span multiple lines, just like a descriptor. In house, we use the SCCS `%Q%` keyword to update the date when a file is changed. A typical copyright line might look like:

```
copyright {1990-%Q% The Regents of the University of
     California}
```

location

This item describes the location of a star definition. The following descriptions are used, for example:

```
location { SDF dsp library }
```

or

```
location { directory }
```

where *directory* is the location of the star. This item is for documentation only.

explanation

This item is used to give longer explanations of the function of the stars. In releases previous to Ptolemy 0.7, this item included troff formatting directives. In Ptolemy 0.7 and later, this item has been superceded by the `htmldoc` item.

htmldoc

This item is used to give longer explanations that include HTML format directives. The Tycho system includes an HTML viewer that can be used to display star documentation. The HTML output of `ptlang` can be viewed by any HTML viewer, but certain features, such as the `<tcl></tcl>` directive are only operational when viewed with Tycho. For complete documentation for the Tycho HTML viewer, see the HTML viewer Help menu.

state

This item is used to define a state or parameter. Recall that by definition, a parameter is the initial value of a state. Here is an example of a state definition:

```
state {
      name { gain }
      type { int }
      default { 10 }
      desc { Output gain. }
      attributes { A_CONSTANT|A_SETTABLE }
}
```

There are five types of subitems that may appear in a state statement, in any order. The `name` field is the name of the state; the `type` field is its type, which may be one of `int`, `float`, `string`, `complex`, `fix`, `intarray`, `floatarray`, `complexarray`, `precision`, or `stringarray`. Case is ignored for the type argument.

The `default` item specifies the default initial value of the state; its argument is either a string (enclosed in quotation marks) or a numeric value. The above entry could equivalently have been written:

```
default { "1.0" }
```

Furthermore, if a particularly long default is required, as for example when initializing an array, the string can be broken into a sequence of strings. The following example shows the default for a `ComplexArray`:

```
default {
"(-.040609,0.0) (-.001628,0.0) (.17853,0.0) (.37665,0.0)"
"(.37665,0.0) (.17853,0.0) (-.001628,0.0) (-.040609,0.0)"
}
```

For complex states, the syntax for the default value is

```
(real, imag)
```

where `real` and `imag` evaluate to integers or floats.

The `precision` state is used to give the precision of fixed-point values. These values may be other states or may be internal to the star. The default can be specified in either of two ways:

- **Method 1**: As a string like “3.2”, or more generally “*m.n*”, where *m* is the number of integer bits (to the left of the binary point) and *n* is the number of fractional bits (to the right of the binary point). Thus length is *m*+*n*.
- **Method 2**: A string like “24/32” which means 24 fraction bits from a total length of 32. This format is often more convenient because the word length often remains constant while the number of fraction bits changes with the normalization being used.

In both cases, the sign bit counts as one of the integer bits, so this number must be at least one.

The `desc` (or `descriptor`) item, which is optional but highly recommended, attaches a descriptor to the state. The same formatting options are available as with the star descriptor.

Finally, the `attributes` keyword specifies state attributes. At present, two attributes are defined for all states: `A_CONSTANT` and `A_SETTABLE` (along with their complements `A_NONCONSTANT` and `A_NONSETTABLE`). If a state has the `A_CONSTANT` attribute, then its value is not modified by the run-time code in the star (it is up to you as the star writer to ensure that this condition is satisfied). States with the `A_NONCONSTANT` attribute may change when the star is run. If a state has the `A_SETTABLE` attribute, then user interfaces (such as `pigi`) will prompt the user for values when directives such as *edit-parameters* are given. States without this attribute are not presented to the user; such states always start with their default values as the initial value. If no attributes are specified, the default is `A_CONSTANT|A_SETTABLE`. Thus, in the above example, the `attributes` directive is unnecessary. The notation “`A_CONSTANT|A_SETTABLE`” indicates a logical “or” of two flags. Confusingly, this means that they both apply (`A_CONSTANT` *and* `A_SETTABLE`).

Code generation stars use a great number of attributes, many specific to the language model for which code is being generated. Read chapter 13, “Code Generation”, and the documentation for the appropriate code generation domain to learn more about these.

Mechanisms for accessing and updating states in C++ methods associated with a star are explained below, in sections 2.4.3 on page 2-21 and 2.4.4 on page 2-23.

An alternative form for the `state` directive is `defstate`. The subitems of the `state` directive are summarized in table 2-2, together with subitems of other directives.

input, output, inout, inmulti, outmulti, inoutmulti

These keywords are used to define a porthole, which may be an input, output, inout (bidirectional) porthole or an input, output, or inout multiporthole. Bidirectional ports are not supported in most domains (The Thor domain is an exception). Like `state`, it contains subitems. Here is an example:

```
input {
      name { signalIn }
      type { complex }
      numtokens { 2 }
      desc {A complex input that consumes 2 input particles.}
}
```

Here, `name` specifies the porthole name. This is a required item. `type` specifies the particle type. The scalar types are `int`, `float`, `fix`, `complex`, `message`, or `anytype`. Again, case does not matter for the type value. The matrix types are `int_matrix_env`, `float_matrix_env`, `complex_matrix_env`, and

item	sub-item	summary	required	page
inmulti, inout, inoutmulti, input	name	name of the port or group of ports	yes	11
	type	data type of input (& output) particles	no	
	descriptor	summary of the function of the input	no	
	numtokens	number of tokens consumed by the port (useful only for dataflow domains)	no	
method, virtual method, inline method, pure method, pure virtual method, inline virtual method	name	the name of the method	yes	15
	access	private, protected, or public	no	
	arglist	the arguments to the method	no	
	type	the return type of the method	no	
	code	C++ code defining the method	if not pure	
outmulti, output	name	name of the port or group of ports	yes	11
	type	data type of output particles	no	
	descriptor	summary of the function of the output	no	
	numtokens	number of tokens produced by the port (useful only for dataflow domains)	no	
state	name	the name of the state variable	yes	9
	type	data type of the state variable	yes	
	default	the default initial value, always a string	yes	
	descriptor	summary of the function of the state	no	
	attributes	hints to the simulator or code generator	no	

TABLE 2-2: Some items used in defining a star have subitems. These are described here.

`fix_matrix_env`. The `type` item may be omitted; the default type is `anytype`. For more information on all of these, please see chapter 4, “Data Types”.

The `numtokens` keyword (it may also be written `num` or `numTokens`) specifies the number of tokens consumed or produced on each firing of the star. This only makes sense for certain domains (SDF, DDF, and BDF); in such domains, if the item is omitted, a value of one is used. For stars where this number depends on the value of a state, it is preferable to leave out the `numtokens` specification and to have the `setup` method set the number of tokens (in the SDF domain and most code generation domains, this is accomplished with the `setSDFParams` method). This item is used primarily in the SDF and code generation domains, and is discussed further in the documentation of those domains.

There is an alternative syntax for the type field of a porthole; this syntax is used in connection with `ANYTYPE` to specify a link between the types of two portholes. The syntax is

```
type { = name  }
```

where `name` is the name of another porthole. This indicates that this porthole inherits its type from the specified porthole. For example, here is a portion of the definition of the SDF `Fork` star:

```
input {
      name{input}
      type{ANYTYPE}
}
outmulti {
      name{output}
      type{= input}
      desc{ Type is inherited from the input. }
}
```

constructor

This item allows the user to specify extra C++ code to be executed in the constructor for the class. This code will be executed *after* any automatically generated code in the constructor that initializes portholes, states, etc. The syntax is:

```
constructor { body }
```

where `body` is a piece of C++ code. It can be of any length. Note that the constructor is invoked only when the class is first instantiated; actions that must be performed before every simulation run should appear in the `setup` or `begin` methods, not the constructor.

conscalls

You may want to have data members in your star that have constructors that require arguments. These members would be added by using the `public`, `private`, or `protected` keywords. If you have such members, the `conscalls` keyword provides a mechanism for passing arguments to the constructors of those members. Simply list the names of the members followed by the list of constructor arguments for each, separated by commas if there is more than one. The syntax is:

```
conscalls { member1(arglist), member2(arglist) }
```

Note that *member1*, and *member2* should have been previously defined in a `public`, `private`, or `protected` section (see page 2-14).

destructor

This item inserts code into the destructor for the class. The syntax is:

```
destructor { body }
```

You generally need a destructor only if you allocate memory in the constructor, `begin` method, or `setup` method; termination functions that happen with every run should appear in the `wrapup` function[1]. The optional keyword `inline` may appear before `destructor`; if so, the destructor function definition appears inline, in the header file. Since the destructor for all stars is virtual, this is only a win when the star is used as a base for derivation.

setup

This item defines the `setup` method, which is called every time the simulation is started, *before* any compile-time scheduling is performed. The syntax is:

```
setup { body }
```

The optional keyword `inline` may appear before the `setup` keyword. It is common for this method to set parameters of input and output portholes, and to initialize states. The code syntax for doing this is explained starting on page 2-16. In some domains, with some targets, the `setup` method may be called more than once during initiation. You must keep this in mind if you use it to allocate or initialize memory.

begin

This item defines the `begin` method, which is called every time the simulation is started, but *after* the scheduler `setup` method is called (i.e., after any compile-time scheduling is performed). The syntax is:

1. Note, however, that wrapup is not called if an error occurs. See page 2-14.

```
begin { body }
```

This method can be used to allocate and initialize memory. It is especially useful when data structures are shared across multiple instances of a star. It is always called exactly once when a simulation is started.

go

This item defines the action taken by the star when it is fired. The syntax is:

```
go { body }
```

The optional keyword `inline` may appear before the `go` keyword. The go method will typically read input particles and write outputs, and will be invoked many times during the course of a simulation. The code syntax for the body is explained starting on page 2-16.

wrapup

This item defines the `wrapup` method, which is called at the completion of a simulation. The syntax is:

```
wrapup { body }
```

The optional keyword `inline` may appear before the `wrapup` keyword. The wrapup method might typically display or store final state values. The code syntax for doing this is explained starting on page 2-16. Note that the `wrapup` method is not invoked if an error occurs during execution. Thus, the `wrapup` method cannot be used reliably to free allocated memory. Instead, you should free memory from the previous run in the `setup` or `begin` method, prior to allocating new memory, and in the destructor.

public, protected, private

These three keywords allow the user to declare extra members for the class with the desired protection. The syntax is:

```
protkey { body }
```

where *protkey* is `public`, `protected`, or `private`. Example, from the `XMgraph` star:

```
protected {
      XGraph graph;
      double index;
}
```

This defines an instance of the class `XGraph`, defined in the Ptolemy kernel, and a

double-precision number. If any of the added members require arguments for their constructors, use the `conscalls` item to specify them.

ccinclude, hinclude

These directives cause the `.cc` file, or the `.h` file, to `#include` extra files. A certain number of files are automatically included, when the preprocessor can determine that they are needed, so they do not need to be explicitly specified. The syntax is:

```
ccinclude { inclist }
hinclude { inclist }
```

where *`inclist`* is a comma-separated list of include files. Each filename must be surrounded either by quotation marks or by "<" and ">" (for system include files like `<math.h>`).

code

This keyword allows the user to specify a section of arbitrary C++ code. This code is inserted into the `.cc` file after the include files but before everything else; it can be used to define static non-class functions, declare external variables, or anything else. The outermost pair of curly braces is stripped. The syntax is:

```
code { body }
```

header

This keyword allows the user to specify an arbitrary set of definitions that will appear in the header file. Everything between the curly braces is inserted into the `.h` file after the include files but before everything else. This can be used, for example, to define classes used by your star. The outermost pair of curly braces is stripped.

method

The `method` item provides a fully general way to specify an additional method for the class of star that is being defined. Here is an example:

```
virtual method {
      name { exec }
      access { protected }
      arglist { "(const char* extraOpts)" }
      type { void }
      code {
            // code for the exec method goes here
      }
}
```

An optional function type specification may appear before the `method` keyword, which must be one of the following:

```
virtual
inline
pure
pure virtual
inline virtual
```

The `virtual` keyword makes a virtual member function. If the `pure virtual` keyword is given, a pure virtual member function is declared (there must be no `code` item in this case). The function type `pure` is a synonym for `pure virtual`. The `inline` function type declares the function to be inline.

Here are the `method` subitems:

`name`: The name of the method. This is a required item.

`access`: The level of access for the method, one of `public`, `protected`, or `private`. If the item is omitted, `protected` is assumed.

`arglist`: The argument list, including the outermost parentheses, for the method as a quoted string. If this is omitted, the method has no arguments.

`type`: The return type of the method. If the return type is not a single identifier, you must put quotes around it. If this is omitted, the return type is `void` (no value is returned).

`code`: The code that implements the method. This is a required item, unless the `pure` keyword appears, in which case this item *cannot* appear.

execime

This item defines the optional `myExecTime()` function, which is used in code generation to specify how many time units are required to execute the star's code. The syntax is:

```
execime { body }
```

The optional keyword `inline` may appear before the `execime` keyword. The *`body`* defines the body of a function that returns an integer value.

codeblock

Codeblocks are parametrized blocks of code for use in code generation stars. Their use and format is discussed in detail in the code generation chapters. The syntax is:

```
codeblock {
     code
     ...
}
```

2.4 Writing C++ code for stars

This section assumes a knowledge of the C++ language; no attempt will be made to

teach the language. We recommend “C++ Primer, Second Edition”, by Stanley Lippman (from Addison-Wesley) for those new to the language. Chapter 3, “Infrastructure for Star Writers”, is also highly recommended reading for those who will be writing stars, since it explains some of the more generic and useful classes defined in the Ptolemy kernel. Many of these are useful in stars.

C++ code segments are an important part of any star definition. They can appear in the `setup`, `begin`, `go`, `wrapup`, `constructor`, `destructor`, `exectime`, `header`, `code`, and `method` directives in the Ptolemy preprocessor. These directives all include a body of arbitrary C++ code, enclosed by curly braces, “`{`” and “`}`”. In all but the `code` and `header` directives, the C++ code between braces defines the body of a method of the star class. Methods can access any member of the class, including portholes (for input and output), states, and members defined with the `public`, `protected`, and `private` directives.

2.4.1 The structure of a Ptolemy star

In general, the task of a Ptolemy star is to receive input particles and/or produce output particles; in addition, there may be side effects (reading or writing files, displaying graphs, or even updating shared data structures). As for all C++ objects, the constructor is called when the star is created, and the destructor is called when it is destroyed. In addition, the `setup` and `begin` methods, if any, are called every time a new simulation run is started, the `go` method (which always exists except for stars like `BlackHole` and `Null` that do nothing) is called each time a star is executed, and the `wrapup` method is called after the simulation run completes without errors.

2.4.2 Reading inputs and writing outputs

The precise mechanism for references to input and output portholes depends somewhat on the domain. This is because stars in the domain `XXX` use objects of class `InXXXPort` and `OutXXXPort` (derived from `PortHole`) for input and output, respectively. The examples we use here are for the SDF domain. See the appropriate domain chapter for variations that apply to other domains.

PortHoles and Particles

In the SDF domain, normal inputs and outputs become members of type `InSDFPort` and `OutSDFPort` after the preprocessor is finished. These are derived from base class `PortHole`. For example, given the following directive in the `defstar` of an SDF star,

```
input {
      name {in}
      type {float}
}
```

a member named `in`, of type `InSDFPort`, will become part of the star.

We are not usually interested in directly accessing these porthole classes, but rather wish to read or write data through the portholes. All data passing through a porthole is derived from base class `Particle`. Each particle contains data of the type specified in the `type` subdirective of the `input` or `output` directive.

The operator "%" operating on a porthole returns a reference to a particle. Consider the following example:

```
go {
      Particle& currentSample = in%0;
      Particle& pastSample = in%1;
      ...
}
```

The right-hand argument to the "%" operator specifies the delay of the access. A zero always means the most recent particle. A one means the particle arriving just before the most recent particle. The same rules apply to outputs. Given an output named `out`, the same particles that are read from `in` can be written to `out` in the same order as follows:

```
go {
      ...
      out%1 = pastSample;
      out%0 = currentSample;
}
```

This works because `out%n` returns a *reference* to a particle, and hence can accept an assignment. The assignment operator for the class `Particle` is overloaded to make a copy of the data field of the particle.

Operating directly on class `Particle`, as in the above examples, is useful for writing stars that accept `anytype` of input. The operations need not concern themselves with the type of data contained by the particle. But it is far more common to operate numerically on the data carried by a particle. This can be done using a cast to a compatible type. For example, since `in` above is of type `float`, its data can be accessed as follows:

```
go {
      Particle& currentSample = in%0;
      double value = double(currentSample);
      ...
}
```

or more concisely,

```
go {
      double value = double(in%0);
      ...
}
```

The expression `double(in%0)` can be used anywhere that a double can be used. In many contexts, where there is no ambiguity, the conversion operator can be omitted:

```
      double value = in%0;
```

However, since conversion operators are defined to convert particles to several types, it is often necessary to indicate precisely which type conversion is desired.

To write data to an output porthole, note that the right-hand side of the assignment operator should be of type `Particle`, as shown in the above example. An operator `<<` is defined for particle classes to make this more convenient. Consider the following example:

```
go {
        float t;
        t = some value to be sent to the output
        out%0 << t;
}
```

Note the distinction between the `<<` operator and the assignment operator; the latter operator copies Particles, the former operator loads data into particles. The type of the right-side operand of `<<` may be `int`, `float`, `double`, `Fix`, `Complex` or `Envelope`; the appropriate type conversion will be performed. For more information on the `Envelope` and `Message` types, please see the chapter “Data Types” on page 4-1.

SDF PortHole parameters

In the above example, where `in%1` was referenced, some special action is required to tell Ptolemy that past input particles are to be saved. Special action is also required to tell the SDF scheduler how many particles will be consumed at each input and produced at each output when a star fires. This information can be provided through a call to `setSDFParams` in the `setup` method. This has the syntax

```
setup {
        name.setSDFParams(multiplicity, past)
}
```

where *`name`* is the name of the input or output porthole, *`multiplicity`* is the number of particles consumed or produced, and *`past`* is the maximum value that *`offset`* can take in any expression of the form *`name%offset`*. For example, if the `go` method references *`name`*`%0` and *`name`*`%1`, then *`past`* would have to be at least one. It is zero by default.

Multiple PortHoles

Sometimes a star should be defined with *n* input portholes or *n* output portholes, where *n* is variable. This is supported by the class `MultiPortHole` and its derived classes. An object of this class has a sequential list of `PortHole`s. For SDF, we have the specialized derived class `MultiInSDFPort` (which contains `InSDFPorts`) and `MultiOutSDFPort` (which contains `OutSDFPorts`).

Defining a multiple porthole is easy, as illustrated next:

```
defstar {
        ...
        inmulti {
                name {input_name}
```

```
            type {input_type}
        }
        outmulti {
            name {output_name}
            type {output_type}
        }
        ...
    }
```

To successively access individual portholes in a `MultiPortHole`, the `MPHIter` iterator class should be used. Iterators are explained in more detail in “Iterators” on page 3-10. Consider the following code segment from the definition of the SDF `Fork` star:

```
input {
    name{input}
    type{ANYTYPE}
}
outmulti {
    name{output}
    type{= input}
}
go {
    MPHIter nextp(output);
    PortHole* p;
    while ((p = nextp++) != 0)
        (*p)%0 = input%0;
}
```

A single input porthole supplies a particle that gets copied to any number of output portholes. The `type` of the output `MultiPortHole` is inherited from the type of the input. The first line of the `go` method creates an `MPHIter` iterator called `nextp`, initialized to point to portholes in `output`. The “++” operator on the iterator returns a pointer to the next porthole in the list, until there are no more portholes, at which time it returns `NULL`. So the `while` construct steps through all output portholes, copying the input particle data to each one.

Consider another example, taken from the SDF `Add` star:

```
inmulti {
    name {input}
    type {float}
}
output {
    name {output}
    type {float}
}
go {
    MPHIter nexti(input);
    PortHole *p;
    double sum = 0.0;
```

```
            while ((p = nexti++) != 0)
                  sum += double((*p)%0);
            output%0 << sum;
      }
```

Again, an `MPHIter` iterator named `nexti` is created and used to access the inputs.

Upon occasion, the `numberPorts` method of class `MultiPortHole`, which returns the number of ports, is useful. This is called simply as *`portname`*`.numberPorts()`, and it returns an `int`.

Type conversion

The type conversion operators and "<<" operators are defined as virtual methods in the base class `Particle`. There are never really objects of class `Particle` in the system; instead, there are objects of class `IntParticle`, `FloatParticle`, `ComplexParticle`, and `FixParticle`, which hold data of type `int`, `double` (not float!), `Complex`, and `Fix`, respectively (there are also `MessageParticle` and a variety of matrix particles, described later). The conversion and loading operators are designed to "do the right thing" when an attempt is made to convert between mismatched types.

Clearly we can convert an `int` to a `double` or `Complex`, or a `double` to a `Complex`, with no loss of information. Attempts to convert in the opposite direction work as follows: conversion of a `Complex` to a `double` produces the magnitude of the complex number. Conversion of a `double` to an `int` produces the greatest integer that is less than or equal to the `double` value. There are also operators to convert to or from `float` and `Fix`.

Each particle also has a virtual `print` method, so a star that writes particles to a file can accept `anytype`.

2.4.3 States

A state is defined by the `state` directive. The star can use a state to store data values, remembering them from one invocation to another. They differ from ordinary members of the star, which are defined using the `public`, `protected`, and `private` directives, in that they have a name, and can be accessed from outside the star in systematic ways. For instance, the graphical interface `pigi` permits the user to set any state with the `A_SETTABLE` attribute to some value prior to a run, using the *edit-params* command. The interpreter provides similar functionality through the `setstate` command. The state attributes are set in the `state` directive. A state may be modified by the star code during a run. The attribute `A_NONCONSTANT` is used as a pragma to mark a state as one that gets modified during a run. There is currently no mechanism for checking the correctness of these attributes.

All states are derived from the base class `State`, defined in the Ptolemy kernel. The derived state classes currently defined in the kernel are `FloatState`, `IntState`, `ComplexState`, `StringState`, `FloatArrayState`, `IntArrayState`, `ComplexArrayState`, and `StringArrayState`.

A state can be used in a star method just like the corresponding predefined data types. As an example, suppose the star definition contains the following directive:

```
state {
```

```
        name { myState }
        type { float }
        default { 1.0 }
        descriptor { Gain parameter. }
}
```

This will define a member of class `FloatState` with default value 1.0. No attributes are defined, so `A_CONSTANT` and `A_SETTABLE`, the default attributes, are assumed. To use the value of a state, it should be cast to type `double`, either explicitly by the programmer or implicitly by the context. For example, the value of this state can be accessed in the `go` method as follows:

```
go {
        output%0 << double(myState) * double(input%0);
}
```

The references to input and output are explained above. The reference to `myState` has an explicit cast to `double`; this cast is defined in `FloatState` class. Similarly, a cast to `int` is available for `IntState`, to `Complex` from `ComplexState`, and to `const char*` for `Stringstate`). In principle, it is possible to rely on the compiler to automatically invoke this cast. However:

Warning: some compilers (notably some versions of g++) may not choose the expected cast. In particular, g++ has been known to cast everything to `Fix` if the explicit cast is omitted in expressions similar to that above. The arithmetic is then performed using fixed-point point computations. This will be dramatically slower than double or integer arithmetic, and may yield unexpected results. It is best to explicitly cast states to the desired form. An exception is with simple assignment statements, like

```
double stateValue = myName;
```

Even g++ gets this right. Explicit casting should be used whenever a state is used in an expression. For example, from the setup method of the `SDFChop` star, in which `use_past_inputs` is an integer state,

```
if ( int(use_past_inputs) )
  input.setSDFParams(int(nread),int(nread)+int(offset)-1);
else
  input.setSDFParams(int(nread),int(nread)-1);
```

Note that the type `Complex` is not a fundamental part of C++. We have implemented a subset of the `Complex` class as defined by several library vendors; we use our own version for maximum portability. Using the `ComplexState` class will automatically ensure the inclusion of the appropriate header files. A member of the `Complex` class can be initialized and operated upon any number of ways. For details, see “The Complex data type” on page 4-1.

A state may be updated by ordinary assignment in C++, as in the following lines

```
double t = expression;
myState = t;
```

This works because the `FloatState` class definition has overloaded the assignment operator ("=") to set its value from a `double`. Similarly, an `IntState` can be set from an `int` and a `StringState` can be set from a `char*` or `const char*` .

2.4.4 Array States

The `ArrayState` classes (`FloatArrayState`, `IntArrayState` and `ComplexArrayState`) are used to store arrays of data. For example,

```
state {
     name { taps }
     type { FloatArray }
     default { "0.0 0.0 0.0 0.0" }
     descriptor { An array of length four. }
}
```

defines an array of type `double` with dimension four, with each element initialized to zero. Quotes must surround the initial values. Alternatively, you can specify a file name with a prefix <. If you have a file named `foo` that contains the default values for an array state, you can write,

```
default { "< foo" }
```

If you expect others to be able to use your star, however, you should specify the default filename using a full path. For instance,

```
default { "< ~/user_name/directory/foo" }
```

For default files installed in the Ptolemy directory tree, this should read:

```
default { "< $PTOLEMY/directory/foo" }
```

The format of the file is also a sequence of data separated by spaces (or newlines, tabs, or commas). File input can be combined with direct data input as in

```
default { "< foo 2.0" }
default { "0.5 < foo < bar" }
```

A "repeat" notation is also supported for `ArrayState` objects: the two value strings

```
default { "1.0 [5]" }
default { "1.0 1.0 1.0 1.0 1.0" }
```

are equivalent. Any integer expression may appear inside the brackets `[]`. The number of elements in an `ArrayState` can be determined by calling its `size` method. The size is not specified explicitly, but is calculated by scanning the default value.

As an example of how to access the elements of an `ArrayState`, suppose `fState` is a `FloatState` and `aState` is a `FloatArrayState`. The accesses, like those in the follow-

ing lines, are routine:

```
fState = aState[1] + 0.5;
aState[1] = (double)fState * 10.0;
aState[0] = (double)fState * aState[2];
```

For a more complete example of the use of `FloatArrayState`, consider the `FIR` star defined below. Note that this is a simplified version of the SDF `FIR` star that does not permit interpolation or decimation.

```
defstar {
      name {FIR}
      domain {SDF}
      desc {
A Finite Impulse Response (FIR) filter.
      }
      input {
            name {signalIn}
            type {float}
      }
      output {
            name {signalOut}
            type {float}
      }
      state {
            name {taps}
            type {floatarray}
            default { "-.04 -.001 .17 .37 .37 .17 -.0018 -.04" }
            desc { Filter tap values. }
      }
      setup {
            // tell the PortHole the maximum delay we will use
            signalIn.setSDFParams(1, taps.size() - 1);
      }
      go {
            double out = 0.0;
            for (int i = 0; i < taps.size(); i++)
                  out += taps[i] * double(signalIn%i);
            signalOut%0 << out;
      }
}
```

Notice the `setup` method; this is necessary to allocate a buffer in the input `PortHole` large enough to hold the particles that are accessed in the `go` method. Notice the use of the `size` method of the `FloatArrayState`.

We now illustrate an `ptcl` interpreter session using the above `FIR` star. Assume there is a galaxy called `singen` that generates a sine wave. you can use it with the `FIR` star, as in:

```
star foop singen
star fir FIR
star printer Printer
```

```
connect foop output fir signalIn
connect fir signalOut printer input
print fir
Star: mainGalaxy.fir
     ...
States in the star fir:
mainGalaxy.fir.taps type: FloatArray
initial value: -.040609 -.001628 .17853 .37665 .37665 .17853
-.001628 -.040609
current value:
0 -0.040609
1 -0.001628
2 .17853
3 .37665
4 .37665
5 .17853
6 -0.001628
7 -0.040609
```

Then you can redefine taps by reading them from a file "`foo`", which contains the data:

```
1.1
-2.2
3.3
-4.4
```

The resulting interpreter commands are:

```
setstate fir taps "<foo 5.5"
print fir
Star: mainGalaxy.fir
     ...
States in the star fir:
mainGalaxy.fir.taps type: FloatArray
initial value: <foo 5.5
current value:
0 1.1
1 -2.2
2 3.3
3 -4.4
4 5.5
PTOLEMY:
```

This illustrates that *both* the contents and the size of a `FloatArrayState` are changed by a `setstate` command. Also, notice that file values may be combined with string values; when

```
< filename
```

occurs in an *initial value*, it is processed exactly as if the whole file were substituted at that

point.

2.5 Modifying PortHoles and States in Derived Classes

When one star is derived from another, it inherits all the states of the base class star. Sometimes we want to modify some aspect of the behavior of a base class state in the derived class. This is done by placing calls to member functions of the state in the constructor of the derived star. Useful functions include `setInitValue` to change the default value, and `setAttibututes` and `clearAttributes` to modify attributes.

When creating new stars derived from stars already in the system, you will often also wish to customize them by adding new ports or states. In addition, you may wish to remove ports or states. Although, strictly speaking, you cannot do this, you can achieve the desired effect by simply hiding them from the user.

The following code will hide a particular state named `statename` from the user:

```
constructor {
      statename.clearAttributes(A_SETTABLE);
}
```

This means that when the user invokes “edit-params” in `pigi`, statename will not appear as one of the parameters of the star. Of course, the state can still be set and used within the code defining the star.

The same effect can be achieved with outputs or inputs. For instance, given an output named `output`, you can use the following code:

```
constructor {
      output.setAttributes(P_HIDDEN);
}
```

This means that when you create an icon for this star, no terminal will appear for this port. This is most useful when `output` is a multiporthole, because this means simply that there will be zero instances of the individual portholes.

This technique can also be used to hide individual portholes, however, the porthole will still be present, so it must be used with caution. Most domains do not allow disconnected portholes, and will flag an error. You can explicitly connect the port within the body of the star (see the kernel manual).

2.6 Programming examples

The following star has no inputs, just an output. The source star generates a linearly increasing or decreasing sequence of float particles on its output. The state *`value`* is initialized to define the value of the first *`output`*. Each time the star `go` method fires, the *`value`* state is updated to store the next *`output`* value. Hence, the attributes of the *`value`* state are set so that the state can be overwritten by the star’s methods. By default, the star will generate the output sequence 0.0, 1.0, 2.0, etc.

```
defstar {
      name { Ramp }
      domain { SDF }
      desc {
```

```
	Generates a ramp signal, starting at "value" (default 0)
	with step size "step" (default 1).
		}
		output {
			name { output }
			type { float }
		}
		state {
			name { step }
			type { float }
			default { 1.0 }
			desc { Increment from one sample to the next. }
		}
		state {
			name { value }
			type { float }
			default { 0.0 }
			desc { Initial (or latest) value output by Ramp. }
			attributes { A_SETTABLE|A_NONCONSTANT }
		}
		go {
			double t = double(value);
			output%0 << t;
			t += step;
			value = t;
		}
	}
```

The next example is the `Gain` star, which multiplies its input by a constant and outputs the result:

```
	defstar {
		name { Gain }
		domain { SDF }
		desc { Amplifier: output is input times "gain" (default 1.0). }
		input {
			name { input }
			type { float }
		}
		output {
			name { output }
			type { float }
		}
		state {
			name { gain }
			type { float }
			default { "1.0" }
			desc { Gain of the star. }
		}
		go {
			output%0 << double(gain) * double(input%0);
		}
	}
```

The following example of the `Printer` star illustrates multiple inputs, `ANYTYPE` inputs, and the use of the `print` method of the `Particle` class.

```
defstar {
	name { Printer }
	domain { SDF }
	inmulti {
		name { input }
		type { ANYTYPE }
	}
	state {
		name { fileName }
		type { string }
		default { "<cout>" }
		desc { Filename for output. }
	}
	hinclude { "pt_fstream.h" }
	protected {
		pt_ofstream *p_out;
	}
	constructor { p_out = 0;}
	destructor { LOG_DEL; delete p_out;}
	setup {
		delete p_out;
		p_out = new pt_ofstream(fileName);
	}
	go {
		pt_ofstream& output = *p_out;
		MPHIter nexti(input);
		PortHole* p;
		while ((p = nexti++) != 0)
			output << ((*p)%0).print() << "\t";
		output << "\n";
	}
}
```

This star is *polymorphic* since it can operate on any type of input. Note that the default value of the output filename is `<cout>`, which causes the output to go to the standard output. This and other aspects of the `pt_ofstream` output stream class are explained below in “Extended input and output stream classes” on page 3-2. The iterator `nexti` used to scan the input is explained in “Iterators” on page 3-10.

2.7 Preventing Memory Leaks in C++ Code

Memory leaks occur when new memory is allocated dynamically and never deallocated. In C programs, new memory is allocated by the `malloc` or `calloc` functions, and deallocated by the `free` function. In C++, new memory is usually allocated by the `new` operator and deallocated by the `delete` or the `delete []` operator. The problem with memory leaks is that they accumulate over time and, if left unchecked, may cripple or even crash a program. We have taken extensive steps to eliminate memory leaks in the Ptolemy software environment by following the guidelines below and by tracking memory leaks with Purify (a

commercial tool from Pure Software Inc.).

One of the most common mistakes leading to memory leaks is applying the wrong `delete` operator. The `delete` operator should be used to free a single allocated class or data value, whereas the `delete []` operator should be used to free an array of data values. In C programming, the `free` function does not make this distinction.

Another common mistake is overwriting a variable containing dynamic memory without freeing any existing memory first. For example, assume that `thestring` is a data member of a class, and in one of the methods (other than the constructor), there is the following statement:

```
thestring = new char[buflen];
```

This code should be

```
delete [] thestring;
thestring = new char[buflen];
```

Using `delete` is not necessary in a class's constructor because the data member would not have been allocated previously.

In writing Ptolemy stars, the `delete` operator should be applied to variables containing dynamic memory in both the star's setup and destructor methods. In the star's constructor method, the variables containing dynamic memory should be initialized to zero. By freeing memory in both the setup and destructor methods, one covers all possible cases of memory leaks during simulation. Deallocating memory in the setup method handles the case in which the user restarts a simulation, whereas deallocating memory in the destructor covers the case in which the user exits a simulation. This includes the cases that arise when error messages are generated. For an example implementation, see the implementation of the `SDFPrinter` star given in Section 2.6.

Another common mistake is not paying attention to the kinds of strings returned by functions. The function `savestring` returns a new string dynamically allocated and should be deleted when no longer used. The `expandPathName`, `tempFileName`, and `makeLower` functions return new strings, as does the `Target::writeFileName` method. Therefore, the strings returned by these routines should be deleted when they are no longer needed, and code such as

```
savestring( expandPathName(s) )
```

is redundant and should be simplified to

```
expandPathName(s)
```

to avoid a memory leak due to not keeping track of the dynamic memory returned by the function `savestring`.

Occasionally, dynamic memory is being used when instead local memory could have been used. For example, if a variable is only used as a local variable inside a method or function and the value of the local variable is not returned or passed to outside the method or function, then it would be better to simply use local memory. For example,

```
char* localstring = new char[len + 1];
if ( person == absent ) return;
strcpy(localstring, otherstring);
delete [] localstring;
```

```
return;
```

could easily return without deallocating `localstring`. The code should be rewritten to use either the `StringList` or `InfString` class, e.g.,

```
InfString localstring;
if ( person == absent ) return;
localstring = otherstring;
return;
```

Both `StringList` and `InfString` can manage the construction of strings of arbitrary size. When a function or method exits, the destructors of the `StringList` and `InfString` variables will automatically be called which will deallocate their memory. Casts have been defined that will convert `StringList` to a `const char*` string and `InfString` to a `const char*` or a `char*` string, so that instances of the `StringList` and `InfString` classes can be passed as is into routines that take character array (string) arguments. A good example of using the `StringList` class is in the function `compile` in the file `$PTOLEMY/src/pigilib/pigiLoader.cc`. A simpler example from the same file is the `noPermission` function which builds up an error message into a single string:

```
StringList sl = msg;
sl << file << ": " << sys_errlist[errno];
ErrAdd(sl);
```

The `errAdd` function takes a `const char*` argument, so `sl` will converted automatically to a `const char*` string by the C++ compiler.

Instead of using the new and delete operators, it is tempting to use constructs like

```
char localstring[buflen + 1];
```

in which `buflen` is a variable, because the compiler will automatically handle the deallocation of the memory. Unfortunately, this syntax is a Gnu extension and not portable to other C++ compilers. Instead, the `StringList` and `InfString` classes should be used, as the previous example involving `localstring` illustrates.

Sometimes the return value from a routine that returns dynamic memory is not stored, and therefore, the pointer to the dynamic memory gets lost. This occurs, for example, in nested function calls. Code such as

```
puts( savestring(s) );
```

should be written as

```
const char* newstring = savestring(s);
puts( newstring );
delete [] newstring;
```

Several places in Ptolemy, especially in the schedulers and targets, rely on the `hashstring` function, which returns dynamic memory. This dynamic memory, however, should *not* be deallocated because it may be reused by other calls to `hashstring`. It is the responsibility of the `hashstring` function to deallocate any memory it has allocated.

Chapter 3. Infrastructure for Star Writers

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3.1 Introduction

The Ptolemy kernel provides a number of C++ classes that are fairly generic and often prove useful to star writers. Some of these are essential, such as those that handle errors. Complete documentation of the kernel classes is given in *The Kernel Manual* volume of *The Almagest*. Here, we summarize only the most generic of these classes, i.e., the ones that are generally useful to star programmers. All of the classes described here may be used in stars, provided that the star writer includes the appropriate header files. For instance, the entry

```
ccinclude { "pt_fstream.h" }
```

will permit the star to create instances of the basic stream classes (described below) in the body of functions that are defined in the star. If the user wishes to create such an instance as a `private`, `protected`, or `public` member of the star, then the header file needs to be included in the `.h` file, specified as done in the line

```
hinclude { "pt_fstream.h" }
```

in the Printer star defined on page 2-28.

The source code for most of classes and functions described in this section can be found in `$PTOLEMY/src/kernel`. The source code is the ultimate reference. Moreover, since this directory is automatically searched for include files when a star is dynamically linked, no special effort is required to specify where to find the include files.

3.2 Handling Errors

Uniform handling of errors is provided by the `Error` class. The `Error` class provides four static methods, summarized in table 3-1. From within a star definition, it is not necessary to explicitly include the `Error.h` header file. A typical use of the class is shown below:

```
Error::abortRun(*this,"this message is displayed");
```

The notation "`Error::abortRun`" is the way static methods are invoked in C++ without having a pointer to an instance of the `Error` class. The first argument tells the error class which object is flagging the error; this is strongly recommended. The name of the object will be printed along with the error message. Note that the `abortRun` call does not cause an immediate halt. It simply marks a flag that the scheduler must test for.

The table uses standard C++ notation to indicate how to use the methods. The type of the return value and the type of the arguments is given, together with an explanation of each. When an argument has the annotation "= *something*," then this argument is optional. If it is

omitted from the call, then the value used will be *something*.

Error class **#include "Error.h"**

method	description
`static void abortRun (`	*signal a fatal error, and request a halt to the run*
`const NamedObj& obj,`	the object triggering the error
`const char*,`	the error message
`const char* = 0,`	optional additional message to concatenate to the error message
`const char* = 0)`	optional additional message to concatenate to the error message
`static void abortRun`	*signal a fatal error, and request a halt to the run*
`const char*,`	the error message
`const char* = 0,`	optional additional message to concatenate to the error message
`const char* = 0)`	optional additional message to concatenate to the error message
`static void error (...)`	*signal an error, without requesting a halt to the run*
`static void message (...)`	*output a message to the user*
`static void warn (...)`	*generate a warning message*

TABLE 3-1: A summary of the static methods in the `Error` class. Each method has two templates, as shown only for the `abortRun` method. The others are the same.

3.3 I/O Classes

Star programmers often need to communicate with the user. The most flexible way to do this is to build a customized, window-based interface, as described in “Using Tcl/Tk” on page 5-1. Often, however, it is sufficient to plot some data or to just construct strings and output them to files or to the standard output[1]. To do the latter, use the classes `pt_ifstream` and `pt_ofstream`, which are derived from the standard C++ stream classes `ifstream` and `ofstream`, respectively. More sophisticated output can be obtained with the `XGraph` class, the histogram classes, and classes that interface to Tk for generating animated, interactive displays. All of these classes are summarized in this section.

3.3.1 Extended input and output stream classes

The `pt_ofstream` class is used in the `Printer` star on page 2-28. Include the header file `pt_fstream.h`. The `pt_ofstream` constructor is invoked in the `setup` method with

1. Note that when users run pigi, the standard output may appear on a window that is buried. The -console option to pigi helps, in that it creates a specific window for the standard output and other interactions with the user. The standard output is much more useful with ptcl, the textual interpreter.

the call to new. It would not do to invoke it in the constructor for the star, since the fileName state would not have been initialized. Notice that the setup method reclaims the memory allocated in previous runs (or previous invocations of the setup method) before creating a new pt_ofstream object. Notice that we are not using a wrapup method to reclaim the memory, since this method is not invoked if an error occurs during a run.

The classes pt_ifstream and pt_ofstream are only a slight extension of the classes ifstream and ofstream. They add the following features:

- First, certain special file names are recognized as arguments to the constructor or to the open method. These file names are <cin>, <cout>, <cerr>, or <clog> (the angle brackets must be part of the string), then the corresponding standard stream of the same name is used for input (pt_ifstream) or output (pt_ofstream). In addition, C standard I/O fans can specify <stdin>, <stdout>, or <stderr>.
- Second, the Ptolemy expandPathName (see table 3-7 on page 3-8) is applied to the filename before it is opened, permitting it to start with ~user or $VAR.
- Finally, if a failure occurs when the file is opened, Error::abortRun is called with an appropriate error message, including the Unix error condition.

These classes can be used for binary character data as well as ASCII.

3.3.2 Generating graphs using the XGraph class

The XGraph class provides an interface to the pxgraph program, used for plotting data on an X window system display. The pxgraph program and all its options are documented in the *User's Manual*. An example of the output from pxgraph is shown in figure 3-1.The most useful methods of the class are summarized in table 3-2.

Using the XGraph class involves an invocation of the initialize method, some number of invocations of the addPoint method, followed by an invocation of the termi-

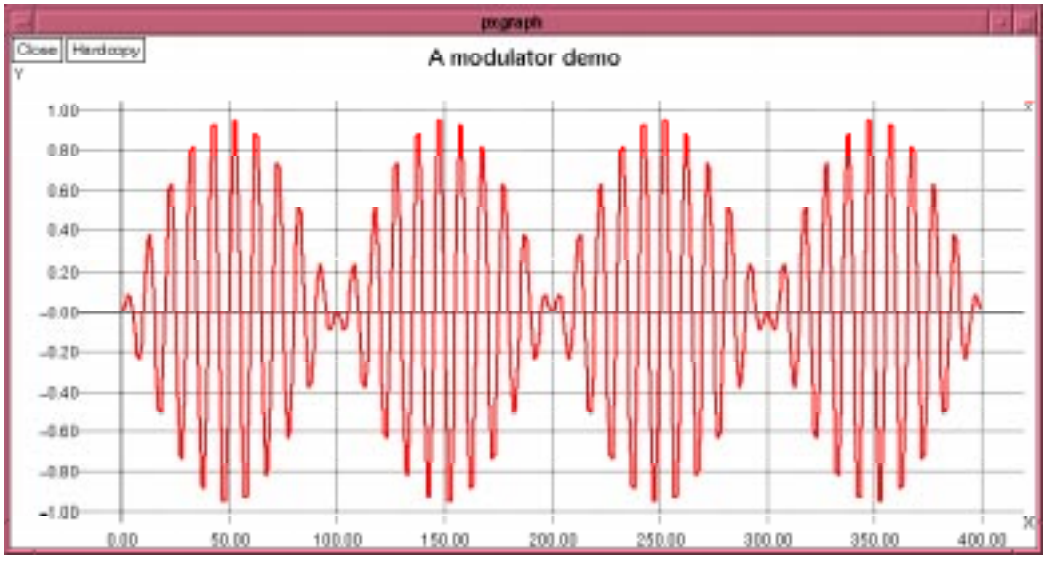

FIGURE 3-1: An example of the output from the pxgraph program, which can be accessed using the XGraph class.

nate method. Multiple data sets (currently up to 64) may be plotted together. They will each be given a distinctive color and/or line pattern. Within each data set, it is possible to break the connecting lines between points by calling the newTrace method.

XGraph class **#include "Display.h"**

method	description
void initialize (	*start a fresh plot*
Block* parent,	pointer to the block using the class
int noGraphs,	the number of data sets to plot
const char* options,	options to pass to the pxgraph program
const char* title,	title to put on the graph
const char* saveFile = 0,	name of a file to save data to
int ignore = 0)	number of initial points to ignore
void addPoint (	*add the next point to the first data set with implicit x position*
float y)	the vertical position
void addPoint (	*add a single point to the first data set*
float x,	the horizontal position of the point to plot
float y)	the vertical position of the point to plot
void addPoint (	*add a single point to a particular data set*
int dataSet,	the number of the data set (starting with 1)
float x,	the horizontal position of the point to plot
float y)	the vertical position of the point to plot
void newTrace (	*start a new trace disconnected from the previous trace*
int dataSet = 1)	the data set for the new trace
void terminate ( )	*plot the data using the pxgraph program*

TABLE 3-2: A summary of the most useful methods of the XGraph class, which provides a simple interface to the pxgraph program, used for plotting data.

3.3.3 Classes for displaying animated bar graphs

The BarGraph class creates a Tk window that displays a bar graph that can be modified dynamically, while a simulation runs. An example with 12 data sets and 8 bars per data set is shown in figure 3-2. The most useful methods of the class are summarized in table 3-3. This class is directly usable only by stars linked into a pigi process, not to stars linked into the interpreter, ptcl. The reason for this is that ptcl does not have the Tk code linked into it. Correspondingly, the class definition source code is in $PTOLEMY/src/pigilib, rather than the more usual $PTOLEMY/src/kernel.

BarGraph class **#include "BarGraph.h"**

method	description
`int setup (`	*start a fresh plot; return FALSE if setup fails*
`Block* parent,`	pointer to the block using the class
`char* desc,`	label for the bar graph
`int numInputs,`	the number of data sets to plot
`int numBars`	the number of bars per data set to show at once
`double top,`	the numerical value that will produce the highest bar
`double bottom,`	the numerical value that will produce the lowest bar
`char* geometry,`	the starting position for the window (e.g. “+0+0” or “-0-0”)
`double width,`	the starting width of the window (in cm)
`double height )`	the starting height of the window (in cm)
`int update (`	*modify or add a bar; return FALSE if it fails*
`int dataSet,`	the number of the data set (starting with 0)
`int bar,`	the horizontal position of the point to plot
`double y )`	the requested height of the bar

TABLE 3-3: A summary of the most useful methods of the `BarGraph` class, which creates animated bar graph charts in a window, and is available to stars running under `pigi`.

3.3.4 Collecting statistics using the histogram classes

The `Histogram` class constructs a histogram of data supplied. The `XHistogram`

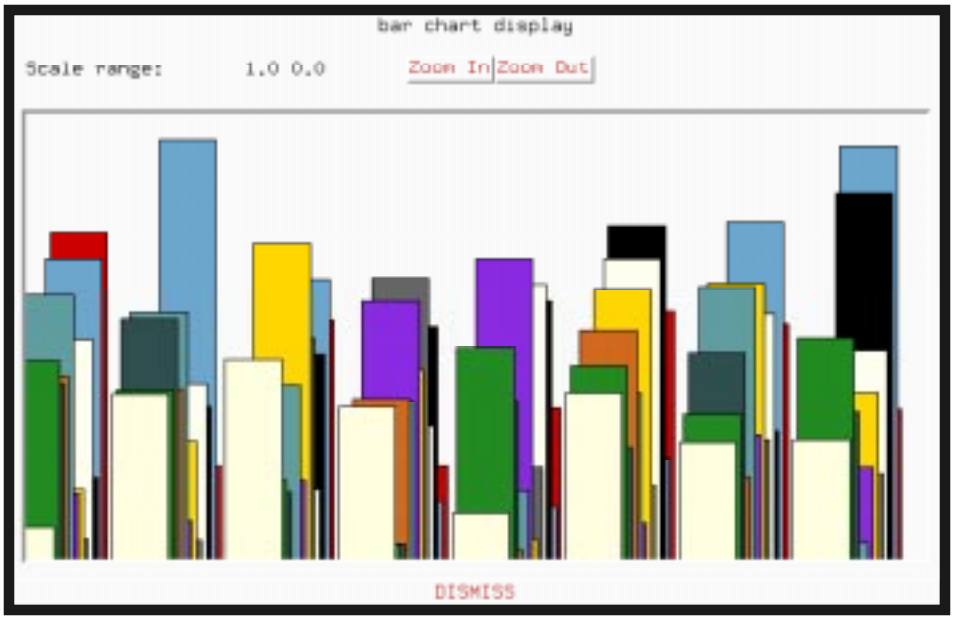

FIGURE 3-2: An example of an animated bar graph created using the `BarGraph` class. This class uses Tk, so it is available under `pigi`, but not under `ptcl`.

class also constructs a histogram, but then plots it using the `pxgraph` program. An example of such a plot is shown in figure 3-3. The most useful methods of both classes are summarized in tables 3-4 and 3-5.

The `Histogram` class counts the number of occurrences of data values that fall within each of a number of bins. Each bin represents a range of numbers. All bins have the same width, and the center of each bin will be an integer multiple of this width. Bin number 0 is always that with the smallest center. Bins are added if new data arrives that does not fit within any of the existing bins. The `getData` method is used to read out the contents of a bin. If you start with bin number 0, and proceed until `getData` returns `FALSE`, you will have read all the bins.

Histogram class **#include "Histogram.h"**

	description
`Histogram (`	*constructor*
`double width = 1.0,`	the width of each bin; bins are centered at integer multiples of this
`int maxBins = 1000 )`	since bins are added as needed, it is wise to limit their number
`void add (`	*add to the count of the bin within which the given data falls*
`double x )`	a data point for the histogram
`int numCounts ( )`	*return the number of data values used so far in the histogram*
`double mean ( )`	*return the average value of all observed data so far*
`double variance ( )`	*return the variance of the observed data so far*
`int getData (`	*get the count for a given bin; return FALSE if the bin is out of range*
`int binno,`	starting at 0, the bin number
`int& count,`	place to store the count for the given bin
`double& bin-Center )`	place to store the center of the given bin

TABLE 3-4: A summary of the most useful methods of the `Histogram` class, which creates histogram charts in a window, and is available to stars running under `pigi`.

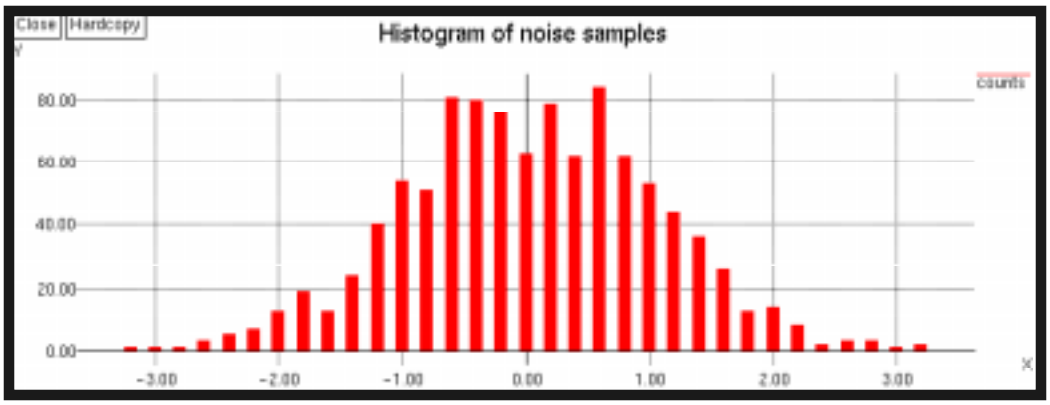

FIGURE 3-3: An example of a histogram generated using the `XHistogram` class.

XHistogram class **#include "Histogram.h"**

method	description
`void initialize (`	*start a fresh histogram*
`Block* parent,`	pointer to the block using the class
`double binWidth,`	the width of each bin; bins are centered at integer multiples of this
`const char* options,`	options to pass to the pxgraph program, in addition to -bar -nl -brw
`const char* title,`	title to put on the histogram
`const char* saveFile,`	name of a file to save data to (or 0 if none)
`int maxBins = 1000 )`	since bins are added as needed, it is wise to limit their number
`void addPoint (`	*add to the count of the bin within which the given data falls*
`double y)`	a data point for the histogram
`int numCounts ( )`	*return the number of data values used so far in the histogram*
`double mean ( )`	*return the average value of all observed data so far*
`double variance ( )`	*return the variance of the observed data so far*
`void terminate ( )`	*plot the histogram using the pxgraph program*

TABLE 3-5: A class for displaying histograms.

3.4 String Functions and Classes

The Ptolemy kernel defines some ordinary functions (not classes) plus two classes that are useful for building and manipulating strings. The non-class string functions are summarized in table 3-6.. These include functions for copying strings, adding strings to a system-

ordinary functions for strings **#include "miscFuncs.h"**

method	description
`char* savestring ( const char* text)`	*create a new copy of the given text and return a pointer to it; the caller must eventually delete the string.*
`const char* hashstring ( const char* text)`	*save a copy of the text in a system-wide hash table, if it isn't already there, and return a pointer to the entry.*
`char* tempFileName ( )`	*return a new, unique temporary file name; the caller must eventually delete the string.*
`const char* expandPathName ( const char* filename)`	*return an expanded version of the filename argument, which may start with "~", "~user", or "$var"; the expanded result is in static storage, and will be overwritten by the next call.*

TABLE 3-6: Non-class (ordinary) functions available in the Ptolemy kernel for string manipulation

wide hash table, creating temporary file names. The non-class pathname functions are summarized in table 3-7. These functions are for expanding file names that might begin with a reference to a user's home directory (`"~username"`) or an shell environment variable (`"$VARIABLE"`). Also provided is a function for verifying that an external program to be invoked is available, and a function for searching the user's path.

ordinary functions for path search **#include "paths.h"**

method	description
`int progNotFound (`	*flag an error and return TRUE if a program is not found*
`const char* program,`	the name of the program to find in the user's path
`const char* extramsg = 0)`	message to add to error message if the program isn't found
`const char* pathSearch (`	*find a file in a Unix-style path, returning the directory name*
`const char* file,`	file name to find in the path
`const char* path = 0)`	if non-zero, the path to use instead of the user's path

TABLE 3-7: Non-class (ordinary) functions available in the Ptolemy kernel for certain pathname manipulations.

Two classes are provided for manipulating strings, `InfString`, and `StringList,` these classes are summarized in figure 3-8.

StringList class **#include "StringList.h"**

method	description
`StringList`	*constructors can take any of the following possible arguments*
`none`	return an empty StringList
`const StringList& s`	copy s and return a new, identical StringList
`char c`	return a StringList with one string of one character
`const char* string`	copy the string and makes a one element StringList containing it

`int i`
`double x`
`unsigned u`
	create an ASCII representation of the number and return a one element StringList with that number as the element

`StringList& operator = arg`	*assignment takes the same types of arguments as the constructors, except "none"*
`StringList& operator << arg`	*add one or more elements to a StringList; this takes the same types of arguments as the constructors, except "none"*
`operator const char*`	*join all elements together and return as a single string;*
`void initialize ( )`	*delete all elements, making the StringList empty*
`int length ( )`	*return the length in characters (sum of the lengths of the elements)*
`int numPieces ( )`	*return the number of elements*
`const char* head ( )`	*return the first element*
`char* newCopy ( )`	*return the concatenated elements in a single newly allocated string; the caller must free the memory allocated.*

InfString class **#include "InfString.h"**

method	description
all `StringList` methods	see above
`operator char*`	*join all elements together and return as a single string;*

TABLE 3-8: A summary of the most useful methods of the `StringList` and `InfString` classes. The `InfString` class inherits all of the methods from `StringList`, adding only the cast to `char*`.

Although these two classes are almost identical in design, their recommended uses are quite different. The first is designed for building up strings without having to be concerned about the ultimate size of the string. New characters can be appended to the string at any time, and memory will be allocated to accommodate them. When you are ready to use the string, perhaps by passing it to a function that expects the standard character array representation of the string, then simply cast the object to `char*`.

In fact, `InfString` is publicly derived from `StringList`, adding only the cast to `char*`. `StringList` is implemented as a list of strings, where the size of the list is not bounded ahead of time. `StringList` is recommended for applications where the list structure is to be preserved. The cast to `char*` in `InfString` destroys the list structure, consolidating all its strings into one contiguous string.

The most useful methods for both classes are summarized in table . Since `InfString` differs by only one operator, we show only that one operator.

A word of warning is in order. If a function or expression returns a `StringList` or `InfString`, and that value is not assigned to a `StringList` or `InfString` variable or reference, and the `(const char*)` or `(char*)` cast is used, it is possible (likely under g++) that the `StringList` or `InfString` temporary will be destroyed too soon, leaving the `const char*` or `char*` pointer pointing to garbage. The solution is to assign the returned value to a local `StringList` or `InfString` before performing the cast. Suppose, for example, that the function `foo` returns an `InfString`. Further, suppose the function `bar` takes a `char*` argument. Then the following code will fail:

```
bar(foo());
```

(Note that the cast to `char*` is implicit). The following code will succeed:

```
InfString x = foo();
bar(x);
```

3.5 Iterators

The `StringList` class is one of several list classes in the Ptolemy kernel. A basic operation on list classes is to sequentially access their members one at a time. This is accomplished using an iterator class, companion to the list class. For the `StringList` class, the iterator is called `StringListIter`. Its methods are summarized in table 3-9. An example program fragment using this is given below:

StringListIter class **#include "StringList.h"**

method	description
`StringList ( StringList& list )`	*constructor* the list over which the iterator will iterate
`const char* next ( )`	*return the next string on the list, or 0 if there are no more*
`const char* operator ++ ( )`	*a synonym for "next"*
`void reset ( )`	*reset the iterator to start at the head again*

TABLE 3-9: An example of an iterator class, used to access the elements of a list class.

```
StringListIter item(myList);
const char* string;
```

```
while ((string = item++) != 0) cout << string << "\n";
```

In this fragment, `myList` is assumed to be a `StringList` previously set up.

3.6 List Classes

The `StringList` class is privately derived from the `SequentialList` class, an extremely useful class used throughout Ptolemy. This class implements a linked list with a running count of the number of elements. It uses the generic pointer technique, with

```
typedef void* Pointer
```

Thus, items in a sequential list can be pointers to any object, with a generic pointer used to access the object. In derived classes, like `StringList`, this generic pointer is converted to a specific type of pointer, like `const char*`. The methods are summarized in table 3-10.

An important point to keep in mind when using a `SequentialList` is that its destructor does not delete the elements in the list. It would not be possible to do so, since it has only a generic pointer. Also, note that random access (by element number, or any other method) can be very inefficient, since it would require sequentially chaining down the list.

`SequentialList` has an iterator class called `ListIter`. The `++` operator (or `next` member function) returns a `Pointer`.

In table 3-11 are two classes privately derived from `SequentialList`, `Queue` and `Stack`. The first of these can implement either a first-in, first-out (FIFO) queue, or a last-in,

SequentialList class **#include "DataStruct.h"**

method	description
`void append (Pointer p)`	*add the element p to the end of the list*
`Pointer elem ( int n )`	*return the n-th element on the list (zero if there are fewer than n)*
`int empty ( )`	*return 1 if empty, 0 if not*
`Pointer getAndRemove ( )`	*return and remove the first element on the list (return zero if empty)*
`Pointer getTailAndRemove ( )`	*return and remove the last element on the list (return zero if empty)*
`Pointer head ( )`	*return the first element on the list (zero if empty)*
`void initialize ( )`	*remove all elements from the list*
`int member (Pointer p)`	*return 1 if the list has a pointer equal to p, 0 if not*
`void prepend (Pointer p)`	*add the element p to the beginning of the list*
`int remove (Pointer p)`	*if the list has a pointer equal to p, remove it, and return 1; 0 if not*
`int size ( )`	*return the number of elements on the list*
`Pointer tail ( )`	*return the last element on the list (zero if empty)*

TABLE 3-10: The most useful basic list structure defined in the Ptolemy kernel.

first-out (LIFO) queue. The second implements a stack, which is also a LIFO queue.

Queue class **#include "DataStruct.h"**

method	description
`Pointer getHead ( )`	*return and remove the first element on the list (return zero if empty)*
`Pointer getTail ( )`	*return and remove the last element on the list (return zero if empty)*
`void initialize ( )`	*remove all elements from the list*
`void putHead (Pointer p)`	*add the element p to the beginning of the list*
`void putTail (Pointer p)`	*add the element p to the end of the list*
`int size ( )`	*return the number of elements on the list*

Stack class **#include "DataStruct.h"**

method	description
`Pointer accessTop ( )`	*return the top of the stack without removing it (return zero if empty)*
`void initialize ( )`	*remove all elements from the list*
`Pointer popTop ( )`	*return and remove the top element from the stack (zero if empty)*
`void pushBottom (Pointer p)`	*add the element p to the bottom of the stack*
`void pushTop (Pointer p)`	*add the element p to the top of the stack*
`int size ( )`	*return the number of elements on the list*

TABLE 3-11: Two classes derived from SequentialList.

3.7 Hash Tables

Hash tables are lists that are indexed by an ASCII string. A “hashing function” is computed from the string to make random accesses reasonably efficient; they are much more efficient, for example, than a linear search over a `SequentialList`. Two such classes are provided in the Ptolemy kernel. The first, `HashTable`, is generic, in that the table entries are of type `Pointer`, and thus can point to any user-defined data structure. The second, `TextTable`, is more specialized; the entries are strings. It is derived from `HashTable`.

The `HashTable` class is summarized in table 3-12 and `TextTable` class is summarized in table 3-13. Only the most useful (and easily used) methods are described. You may want to refer to the source code for more information. The `HashTable` class has a standard iterator called `HashTableIter`, where the `next` method and `++` operator return a pointer to class `HashEntry`. This class has a `const char* key()` method that returns the key for the entry, and a `Pointer value()` method that returns a pointer to the entry. `TextTable` has an iterator called `TextTableIter`, where the `next` method and `++` operator return type `const char*`.

HashTable class **#include "HashTable.h"**

method	description
`void clear ( )`	*empty the table*
`virtual void cleanup ( Pointer p)`	*does nothing; in derived classes, this might deallocate memory*
`int hasKey ( const char* key )`	*return 1 if the given key is in the table, 0 otherwise*
`void insert ( const char* key, Pointer data )`	*insert an entry; any previous entry with the same key is replaced, and the cleanup method is called so that in derived classes, its memory can be deallocated.*
`Pointer lookup ( const char* key)`	*lookup an entry; in a derived class, this could be overloaded to return a pointer of a more specific type.*
`int remove ( const char* key)`	*remove the entry with the given key from the table; note that the object pointed to by the entry is not deallocated.*
`int size ( )`	*return the number of entries in the hash table*

TABLE 3-12: A summary of the most useful methods of the HashTable class

Sophisticated users will often want to derive new classes from `HashTable`. The reason is that the methods that look up data in the table can be defined to return pointers of the appropriate type. Moreover, the deallocation of memory when an entry is deleted or the table itself is deleted can be automated. `TextTable` is a good example of such a derived class. This is not possible with the generic `HashTable` class, because the `Pointer` type does not give enough information to know what destructor to invoke. Thus, when using the generic `HashTable` class, the user should explicitly delete the objects pointed to by the `Pointer` if they were dynamically created and are no longer needed. A detailed example that directly uses the `HashTable` class, without defining a derived class, is given in the next section. In that exam-

ple, the `Pointer` entries point to stars in a universe, so they should not be deleted when the entries in the table are deleted. Their memory will be deallocated when the universe is deleted.

TextTable class **#include "HashTable.h"**

method	description
`void clear ( )`	*empty the table*
`void cleanup ( Pointer p)`	*deallocate the string pointed to by p*
`int hasKey ( const char* key )`	*return 1 if the given key is in the table, 0 otherwise*
`void insert ( const char* key, const char* string )`	*create an entry containing a copy of string; any previous entry with the same key is replaced, and the cleanup method is called to deallocate its memory.*
`const char* lookup ( const char* key)`	lookup an entry with the given key; return 0 if there is no such entry.
`int remove ( const char* key)`	remove the entry with the given key from the table and deallocated its memory.
int **size** ( )	return the number of entries in the hash table

TABLE 3-13: A summary of the most useful methods of the `HashTable` and `TextTabl` classes.

In some future version, `HashTable` might be reimplemented using templates.

3.8 Sharing Data Structures Across Multiple Stars

It is sometimes desirable to have a set of stars that share and manipulate a common data structure[1]. A simple way to accomplish this is to define a star that contains a static member. Suppose, for example, you wish to define a class of stars that create a shared list of pointers, one to each instance of this type of star. Thus, every star of this type would be able to access every other star of this type. Consider the following implementation:

```
defstar {
      name { Share }
      domain { SDF }
      desc { A star with a shared data structure }
      hinclude { “DataStruct.h” }
      private {
          static SequentialList starList;
      }
      output {
          name { howmany }
          type { int }
      }
      code {
```

1. See the SDFWriteVar and SDFReadVar stars for a similar implementation.

```
            SequentialList SDFShare::starList;
        }
        begin {
            starList.append(this);
        }
        go {
            howmany%0 << starList.size();
        }
        wrapup {
            starList.initialize();
        }
}
```

This star has a static private member of type `SequentialList` with name `starList.` The "`static`" in C++ ensures that there will be no more than one instance of the `SequentialList` object. That instance will be accessible to every instance of the star, but not to any other object (because the member is private). That one instance is actually declared by the lines:

```
        code {
            SequentialList SDFShare::starList;
        }
```

The declaration will get put into the file `SDFShare.cc` by the preprocessor. Notice that the class name of the star is `SDFShare` not just `Share`. The `begin` method simply adds to the sequential list a pointer to the star that invoked the `begin` method (`this`). Note that you should use the `begin` method here rather than the `setup` method because the `begin` method is always invoked exactly once, while the `setup` method might be invoked more than once when the simulation starts up. The `go` method sends to the output (named `howmany`) the size of the list. This will be equal to the number of stars of this type in the universe.

The `wrapup` method has the only tricky part of this code. It reinitializes the `SequentialList` so that subsequent runs do not just simply add to a list created by previous runs. However, note that the wrapup method will not be invoked if an error occurs during the run. `Pigi` ensures correct operation nonetheless by deleting all instances of the stars and recreating them if an error occurred on the previous run. Thus, between invocations of the `begin` method, either the `wrapup` method or the constructor for the star (and all its members) will be invoked. The constructor for `SequentialList` also initializes the list, so the list is always initialized before the first `begin` method is called.

The above approach is somewhat limited. You may want more than one type of star to share a data structure. In this case, you should create a common base class for all the stars that will share the data structure. The shared data structure should be a protected member, rather than a private member, so that it is accessible to derived stars.

Alternatively, you might want arbitrary subsets of stars to share distinct data structures, one for each subset. This can be accomplished by defining a static list that is indexed by a string, and using a parameter in the star to identify to which subset it belongs. An efficient data structure to use for this is the `HashTable`. So for example, suppose we wanted to modify the above star to create lists of stars with common values of a parameter "mySubset", and to output the number of stars in their subset. The above code becomes:

```
defstar {
```

```
        name { BetterShare }
        domain { SDF }
        desc { A star with a shared data structure }
        hinclude { "DataStruct.h" }
        hinclude { "HashTable.h" }
        output {
            name { howmany }
            type { int }
        }
        state {
            name { mySubset }
            default { "subset A" }
            type { string }
        }
        private {
            static HashTable listOfLists;
            SequentialList* myList;
        }
        code {
            HashTable SDFBetterShare::listOfLists;
        }
        begin {
            if (listOfLists.hasKey((char*)mySubset)) {
              myList = listOfLists.lookup((char*)mySubset);
            } else {
              myList = new SequentialList;
              listOfLists.insert((char*)mySubset,myList);
            }
            myList->append(this);
        }
        go {
            howmany%0 << myList->size();
        }
        wrapup {
            if (listOfLists.hasKey((char*)mySubset)) {
              listOfLists.remove((char*)mySubset);
              delete myList;
            }
        }
}
```

In addition to the static private member `listOfLists`, we also have a pointer `myList` to a `SequentialList`. The `begin` method is a bit more complicated now. It first checks to see whether an entry in the hash table has already been created with a key equal to the value of the state “mySubset”. If it has, then the `SequentialList` pointer `myList` is set equal to the value of that entry. If it has not, then a new `SequentialList` is allocated and inserted into the hash table with the appropriate key. The last action is simply to insert a pointer to the star instance into `myList`.

The `go` method is similar to before.

The `wrapup` method is slightly more complicated, because it needs to free the memory allocated when the new `SequentialList` was allocated. However, it should free that

memory only once, and there may be several star instances pointing to it. Thus, it first checks the hash table to see whether there exists an entry with key equal to `mySubset`. If there does, then it removes that entry and deletes the `SequentialList myList`.

3.9 Using Random Numbers

Ptolemy uses the Gnu library routines for the random number generation. Refer to Volume II of the Art of Computer Programming by Knuth for details about the method. There are built-in classes for some popular distributions: uniform, exponential, geometric, discrete uniform, normal, log-normal, and so on. These classes use a common basic random number generation routine which is realized in the `ACG` class. Here are some examples of using random numbers.

The first example is the part of the DE `Poisson` star. See the DE chapter for details on how to write DE stars.

```
hinclude { <NegExp.h> }
ccinclude { <ACG.h> }
protected {
      NegativeExpntl *random;
}
// declare the static random-number generator in the .cc file
code {
      extern ACG* gen;
}
constructor {
      random = NULL;
}
destructor {
      if(random) delete random;
}
setup {
      if(random) delete random;
      random = new NegativeExpntl(double(meanTime),gen);
      DERepeatStar :: setup();
}
go {
       ......
      // Generate an exponential random variable.
      double p = (*random)();
       ......
}
```

The built-in class for an exponentially distributed random numbers is `NegativeExpntl`.

The Ptolemy kernel provides a single object to generate a stream of random numbers; the global variable `gen` (a poor choice of name, perhaps) is a pointer to it. We create an instance of the `NegativeExpntl` class in the `setup` method, not in the constructor since Ptolemy allows you to change the seed of the random number generator. When the user changes the seed of the random number generator, the object pointed to by `gen` is deleted and re-created, so all objects such as the one pointed to by `random` in this star become invalid.

Finally, we can read a random number of the specific type by calling operator `()` of the `NegativeExpnl` class.

This example uses a uniformly distributed random number.

```
hinclude { <Uniform.h> }
ccinclude { <ACG.h> }
protected {
      Uniform *random;
}
// declare the extern random-number generator in the .cc file
code {
      extern ACG* gen;
}
constructor {
      random = NULL;
}
destructor {
      if(random) delete random;
}
setup {
      if(random) delete random;
      random = new Uniform(0,double(output.numberPorts()),gen);
}
go {
      ......
      double p = (*random)();
      ......
}
```

You may notice that the two examples above are very similar in nature. You can get another kind of distribution for the random numbers, by including the appropriate library file in the `.h` file and by creating the instance with the right parameters in the `setup` method.

Chapter 4. Data Types

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4.1 Introduction

Stars communicate by sending objects of type `Particle`. A basic set of types, including scalar and array types, built on the `Particle` class, is built into the Ptolemy kernel. Since all of these particle types are derived from the same base class, it is possible to write stars that operate on any of them (by referring only to the base class). It is also possible to define new types that contain arbitrary C++ objects.

There are currently eleven key data types defined in the Ptolemy kernel. There are four numeric scalar types—complex, fixed-point, double precision floating-point, and integer—described in Section 4.2. Ptolemy supports a limited form of user-defined type—the *Message* type, described in Section 4.3. Each of the scalar numeric types has an equivalent matrix type, which uses a more complex version of the user-defined type mechanism; they are described in Section 4.4.

There are two experimental types included in the basic set, containing strings and file references, described in Section 4.5. Ptolemy allows stars to be written that will read and write particles of any type; this mechanism is described in Section 4.6. Finally, some experimental types that are not officially supported by Ptolemy are described in Section 4.7.

4.2 Scalar Numeric Types

There are four scalar numeric data types defined in the Ptolemy kernel: complex, fixed-point, double precision floating-point, and integer. All of these four types can be read from and written to portholes as described in “Reading inputs and writing outputs” on page 2-17. The floating-point and integer data types are based on the standard C++ `double` and `int` types, and need no further explanation. To support the other two types, the Ptolemy kernel contains a `Complex` class and a `Fix` class, which are described in the rest of this section.

4.2.1 The Complex data type

The `Complex` data type in Ptolemy contains real and imaginary components, each of which is specified as a double precision floating-point number. The notation used to represent

a complex number is a two number pair: (real, imaginary)—for example, (1.3,-4.5) corresponds to the complex number 1.3 – 4.5*j*. `Complex` implements a subset of the functionality of the complex number classes in the cfront and libg++ libraries, including most of the standard arithmetic operators and a few transcendental functions.

Constructors:

`Complex()`

Create a complex number initialized to zero—that is, (0.0, 0.0). For example,

```
Complex C;
```

`Complex(double real, double imag)`

Create a complex number whose value is (real, imag). For example,

```
Complex C(1.3,-4.5);
```

`Complex(const Complex& arg)`

Create a complex number with the same value as the argument (the copy constructor). For example,

```
Complex A(complexSourceNumber);
```

Basic operators:

The following list of arithmetic operators modify the value of the complex number. All functions return a reference to the modified complex number (`*this`).

```
Complex& operator = (const Complex& arg)
Complex& operator += (const Complex& arg)
Complex& operator -= (const Complex& arg)
Complex& operator *= (const Complex& arg)
Complex& operator /= (const Complex& arg)
Complex& operator *= (double arg)
Complex& operator /= (double arg)
```

There are two operators to return the real and imaginary parts of the complex number:

```
double real() const
double imag() const
```

Non-member functions and operators:

The following one- and two-argument operators return a new complex number:

```
Complex operator + (const Complex& x, const Complex& y)
Complex operator - (const Complex& x, const Complex& y)
Complex operator * (const Complex& x, const Complex& y)
```

```
Complex operator * (double x, const Complex& y)

Complex operator * (const Complex& x, double y)

Complex operator / (const Complex& x, const Complex& y)

Complex operator / (const Complex& x, double y)

Complex operator - (const Complex& x)
```
Return the negative of the complex number.

```
Complex conj (const Complex& x)
```
Return the complex conjugate of the number.

```
Complex sin(const Complex& x)

Complex cos(const Complex& x)

Complex exp(const Complex& x)

Complex log(const Complex& x)

Complex sqrt(const Complex& x)

Complex pow(double base, const Complex& expon)

Complex pow(const Complex& base, const Complex& expon)
```

Other general operators:

```
double abs(const Complex& x)
```
Return the absolute value, defined to be the square root of the norm.

```
double arg(const Complex& x)
```
Return the value arctan(x.imag()/x.real()).

```
double norm(const Complex& x)
```
Return the value x.real() * x.real() + x.imag() * x.imag().

```
double real(const Complex& x)
```
Return the real part of the complex number.

```
double imag(const Complex& x)
```
Return the imaginary part of the complex number.

Comparison Operators:

```
int operator != (const Complex& x, const Complex& y)

int operator == (const Complex& x, const Complex& y)
```

4.2.2 The fixed-point data type

The fixed-point data type is implemented in Ptolemy by the `Fix` class. This class supports a two's complement representation of a finite precision number. In fixed-point notation, the partition between the integer part and the fractional part—the binary point—lies at a fixed

position in the bit pattern. Its position represents a trade-off between precision and range. If the binary point lies to the right of all bits, then there is no fractional part.

Constructing Fixed-point variables

Variables of type `Fix` are defined by specifying the word length and the position of the binary point. At the user-interface level, precision is specified either by setting a fixed-point parameter to a "(*value*, *precision*)" pair, or by setting a `precision` parameter. The former gives the value and precision of some fixed-point value, while the latter is typically used to specify the internal precision of computations in a star.

In either case, the syntax of the precision is either "*x.y*" or "*m*/*n*", where *x* is the number of integer bits (including the sign bit), *y* and *m* are the number of fractional bits, and *n* is the total number of bits. Thus, the total number of bits in the fixed-point number (also called its *length*) is *x*+*y* or *n*. For example, a fixed-point number with precision "3.5" has a total length of 8 bits, with 3 bits to the left and 5 bits to the right of the binary point.

At the source code level, methods working on `Fix` objects either have the precision passed as an "*x.y*" or "*m*/*n*" string, or as two C++ integers that specify the total number of bits and the number of integer bits including the sign bit (that is, *n* and *x*). For example, suppose you have a star with a precision parameter named *precision*. Consider the following code:

```
Fix x = Fix(((const char *) precision));
if (x.invalid())
       Error::abortRun(*this, "Invalid precision");
```

The "precision" parameter is cast to a string and passed as a constructor argument to the `Fix` class. The error check verifies that the precision was valid.

There is a maximum value for the total length of a `Fix` object which is specified by the constant `FIX_MAX_LENGTH` in the file `$PTOLEMY/src/kernel/Fix.h`. The current value is 64 bits. Numbers in the `Fix` class are represented using two's complement notation, with the sign bit stored in the bits to the left of the binary point. There must always be at least one bit to the left of the binary point to store the sign.

In addition to its value, each `Fix` object contains information about its precision and error codes indicating overflow, divide-by-zero, or bad format parameters. The error codes are set when errors occur in constructors or arithmetic operators. There are also fields to specify

a. whether rounding or truncation should take place when other `Fix` values are assigned to it—truncation is the default

b. the response to an overflow or underflow on assignment—the default is saturation (see page 4-6).

Warning

The `Fix` type is still experimental.

Fixed-point states

State variables can be declared as `Fix` or `FixArray`. The precision is specified by an associated precision state using either of two syntaxes:

- Specifying just a value itself in the dialog box creates a fixed-point number with the default length of 24 bits and with the position of the binary point set as required to store the integer value. For example, the value 1.0 creates a fixed-point object with precision 2.22, and the value 0.5 would create one with precision 1.23.
- Specifying a (value, precision) pair create a fixed-point number with the specified precision. For example, the value (2.546, 3.5) creates a fixed-point object by casting the double 2.546 to a `Fix` with precision 3.5.

Fixed-point inputs and outputs

`Fix` types are available in Ptolemy as a type of `Particle`. The conversion from an `int` or a `double` to a `Fix` takes place using the `Fix::Fix(double)` constructor which makes a `Fix` object with the default word length of 24 bits and the number of integer bits as needed required by the value. For instance, the `double` 10.3 will be converted to a `Fix` with precision 5.19, since 5 is the minimum number of bits needed to represent the integer part, 10, including its sign bit.

To use the `Fix` type in a star, the type of the portholes must be declared as "`fix`". Stars that receive or transmit fixed-point data have parameters that specify the precision of the input and output in bits, as well as the overflow behavior. Here is a simplified version of `SDFAddFix` star, configured for two inputs:

```
defstar {
      name { AddFix }
      domain {SDF}
      derivedFrom{ SDFFix }
      input {
            name { input1 }
            type { fix }
      }
      input {
            name { input2 }
            type { fix }
      }
      output {
            name { output }
            type { fix }
      }
      defstate {
            name { OutputPrecision }
            type { precision }
            default { 2.14 }
      desc {
Precision of the output in bits and precision of the accumulation.
When the value of the accumulation extends outside of the precision,
the OverflowHandler will be called.
      }
}
```

(Note that the real `AddFix` star supports any number of inputs.) By default, the precision used by this star during the addition will have 2 bits to the left of the binary point and 14 bits to the

right. Not shown here is the state OverflowHandler, which is inherited from the SDFFix star and which defaults to saturate—that is, if the addition overflows, then the result saturates, pegging it to either the largest positive or negative number representable. The result value, sum, is initialized by the following code:

```
protected {
      Fix sum;
}
begin {
      SDFFix::begin();

      sum = Fix( ((const char *) OutputPrecision) );
      if ( sum.invalid() )
            Error::abortRun(*this, "Invalid OutputPrecision");
      sum.set_ovflow( ((const char*) OverflowHandler) );
      if ( sum.invalid() )
            Error::abortRun(*this, "Invalid OverflowHandler");
}
```

The begin method checks the specified precision and overflow handler for correctness. Then, in the go method, we use sum to calculate the result value, thus guaranteeing that the desired precision and overflow handling are enforced. For example,

```
go {
      sum.setToZero();
      sum += Fix(input1%0);
      checkOverflow(sum);
      sum += Fix(input2%0);
      checkOverflow(sum);
      output%0 << sum;
}
```

(The checkOverflow method is inherited from SDFFix.) The protected member sum is an *uninitialized* Fix object until the begin method runs. In the begin method, it is given the precision specified by OutputPrecision. The go method initializes it to zero. If the go method had instead assigned it a value specified by another Fix object, then it would acquire the precision of that other object—at that point, it would be *initialized*.

Assignment and overflow handling

Once a Fix object has been initialized, its precision does not change as long as the object exists. The assignment operator is overloaded so that it checks whether the value of the object to the right of the assignment fits into the precision of the left object. If not, then it takes the appropriate overflow response is taken and set the overflow error bit.

If a Fix object is created using the constructor that takes no arguments, as in the protected declaration above, then that object is an uninitialized Fix; it can accept any assignment, acquiring not only its value, but also its precision and overflow handler.

The behavior of a Fix object on an overflow depends on the specifications and the behavior of the object itself. Each object has a private data field that is initialized by the constructor; when there is an overflow, the overflow_handler looks at this field and uses the

specified method to handle the overflow. This data field is set to `saturate` by default, and can be set explicitly to any other desired overflow handling method using a function called `set_ovflow(<keyword>)`. The keywords for overflow handling methods are: `saturate` (default), `zero_saturate`, `wrapped`, `warning`. `saturate` replaces the original value is replaced by the maximum (for overflow) or minimum (for underflow) value representable given the precision of the `Fix` object. `zero_saturate` sets the value to zero.

Explicitly casting inputs

In the above example, the first line of the `go` method assigned the input to the protected member `sum`, which has the side-effect of quantizing the input to the precision of `sum`. We could have alternatively written the `go` method as follows:

```
go {
      sum = Fix(input1%0) + Fix(input2%0);
      output%0 << sum;
}
```

The behavior here is significantly different: the inputs are added using their own native precision, and only the result is quantized to the precision of `sum`.

Some stars allow the user to select between these two different behaviors with a parameter called *ArrivingPrecision*. If set to `YES`, the input particles are not explicitly cast; they are used as they are; if set to `NO`, the input particles are cast to an internal precision, which is usually specified by another parameter.

Here is the (abbreviated) source of the `SDFGainFix` star, which demonstrates this point:

```
defstar {
      name { GainFix }
      domain { SDF }
      derivedFrom { SDFFix }
      desc {
This is an amplifier; the fixed-point output is the fixed-point input
multiplied by the "gain" (default 1.0). The precision of "gain", the
input, and the output can be specified in bits.
      }
      input {
            name { input }
            type { fix }
      }
      output {
            name { output }
            type { fix }
      }
      defstate {
            name { gain }
            type { fix }
            default { 1.0 }
            desc { Gain of the star. }
      }
```

```
      defstate {
            name { ArrivingPrecision }
            type {int}
            default {"YES"}
            desc {
Flag indicating whether or no to use the arriving particles as they
are: YES keeps the same precision, and NO casts them to the precision
specified by the parameter "InputPrecision". }
      }
      defstate {
            name { InputPrecision }
            type { precision }
            default { 2.14 }
            desc {
Precision of the input in bits. The input particles are only cast
to this precision if the parameter "ArrivingPrecision" is set to NO.
            }
      }
      defstate {
            name { OutputPrecision }
            type { precision }
            default { 2.14 }
            desc {
Precision of the output in bits.
This is the precision that will hold the result of the arithmetic
operation on the inputs.
When the value of the product extends outside of the precision,
the OverflowHandler will be called.
      }
      protected {
            Fix fixIn, out;
      }
      begin {
            SDFFix::begin();

            if ( ! int(ArrivingPrecision) ) {
               fixIn = Fix( ((const char *) InputPrecision) );
               if(fixIn.invalid())
                  Error::abortRun( *this, "Invalid InputPrecision" );
            }

            out = Fix( ((const char *) OutputPrecision) );
            if ( out.invalid() )
               Error::abortRun( *this, "Invalid OutputPrecision" );
            out.set_ovflow( ((const char *) OverflowHandler) );
               if(out.invalid())
                  Error::abortRun( *this,"Invalid OverflowHandler" );
      }
      go {
            // all computations should be performed with out since
            // that is the Fix variable with the desired overflow
            // handler
            out = Fix(gain);
            if ( int(ArrivingPrecision) ) {
```

```
                out *= Fix(input%0);
            }
            else {
                fixIn = Fix(input%0);
                out *= fixIn;
            }
            checkOverflow(out);
            output%0 << out;
        }
        // a wrap-up method is inherited from SDFFix
        // if you defined your own, you should call SDFFix::wrapup()
}
```

Note that the SDFGainFix star and many of the Fix stars are derived from the star SDFFix. SDFFix implements commonly used methods and defines two states: OverflowHandler selects one of four overflow handlers to be called each time an overflow occurs; and ReportOverflow, which, if true, causes the number and percentage of overflows that occurred for that star during a simulation run to be reported in the wrapup method.

Constructors:

`Fix()` Create a Fix number with unspecified precision and value zero.

`Fix(int length, int intbits)`
Create a Fix number with total word length of length bits and intbits bits to the left of the binary point. The value is set to zero. If the precision parameters are not valid, then an error bit is internally set so that the invalid method will return TRUE.

`Fix(const char* precisionString)`
Create a Fix number whose precision is determined by precisionString, which has the syntax "*leftbits.rightbits*", where *leftbits* is the number of bits to the left of the binary point and *rightbits* is the number of bits to the right of the binary point, or "*rightbits/totalbits*", where *totalbits* is the total number of bits. The value is set to zero. If the precisionString is not in the proper format, an error bit is internally set so that the invalid method will return TRUE.

`Fix(double value)`
Create a Fix with the default precision of 24 total bits for the word length and set the number of integer bits to the minimum needed to represent the integer part of the number value. If the value given needs more than 24 bits to represent, the value will be clipped and the number stored will be the largest possible under the default precision (i.e. saturation occurs). In this case an internal error bit is set so that the ovf_occurred method will return TRUE.

`Fix(int length, int intbits, double value)`
Create a Fix with the specified precision and set its value to the given value. The number is rounded to the closest representable number

given the precision. If the precision parameters are not valid, then an error bit is internally set so that the `invalid` method will return `TRUE`.

`Fix(const char* precisionString, double value)`
Same as the previous constructor except that the precision is specified by the given `precisionString` instead of as two integer arguments. If the precision parameters are not valid, then an error bit is internally set so that the `invalid()` method will return true when called on the object.

`Fix(const char* precisionString, uint16* bits)`
Create a `Fix` with the specified precision and set the bits precisely to the ones in the given `bits`. The first word pointed to by `bits` contains the most significant 16 bits of the representation. Only as many words as are necessary to fetch the bits will be referenced from the `bits` argument. For example: `Fix("2.14",bits)` will only reference `bits[0]`.

This constructor gets very close to the representation and is meant mainly for debugging. It may be removed in the future.

`Fix(const Fix& arg)`
Copy constructor. Produces an exact duplicate of `arg`.

`Fix(int length, int intbits, const Fix& arg)`
Read the value from the `Fix` argument and set to a new precision. If the precision parameters are not valid, then an error bit is internally set so that the `invalid` method will return true when called on the object. If the value from the source will not fit, an error bit is set so that the `ovf_occurred` method will return `TRUE`.

Functions to set or display information about the Fix number:

`int len() const`
Return the total word length of the Fix number.

`int intb() const`
Return the number of bits to the left of the binary point.

`int precision() const`
Return the number of bits to the right of the binary point.

`int overflow() const`
Return the code of the type of overflow response for the `Fix` number. The possible codes are:
`0` - `ovf_saturate`,
`1` - `ovf_zero_saturate`,
`2` - `ovf_wrapped`,
`3` - `ovf_warning`,
`4` - `ovf_n_types`.

`int roundMode() const`
: Return the rounding mode: `1` for rounding, `0` for truncation.

`int signBit() const`
: Return `TRUE` if the value of the `Fix` number is negative, `FALSE` if it is positive or zero.

`int is_zero()`
: Return `TRUE` if the value of the `Fix` number is zero.

`double max()`
: Return the maximum value representable using the current precision.

`double min()`
: Return the minimum value representable using the current precision.

`double value()`
: The value of the `Fix` number as a double.

`void setToZero()`
: Set the value of the `Fix` number to zero.

`void set_overflow(int value)`
: Set the overflow type.

`void set_rounding(int value)`
: Set the rounding type: `TRUE` for rounding, `FALSE` for truncation.

`void initialize()`
: Discard the current precision format and set the `Fix` number to zero.

There are a few functions for backward compatibility:

`void set_ovflow(const char*)`
: Set the overflow using a name.

`void Set_MASK(int value)`
: Set the rounding type. Same functionality as `set_rounding()`.

Comparison function:

`int compare (const Fix& a, const Fix& b)`
: Compare two `Fix` numbers. Return –1 if $a < b$, 0 if $a = b$, 1 if $a > b$.

The following functions are for use with the error condition fields:

`int ovf_occurred()`
: Return `TRUE` if an overflow has occurred as the result of some operation like addition or assignment.

`int invalid()`
: Return `TRUE` if the current value of the `Fix` number is invalid due to it having an improper precision format, or if some operation caused a

divide by zero.

`int dbz()` Return `TRUE` if a divide by zero error occurred.

`void clear_errors()`
Reset all error bit fields to zero.

Operators:

`Fix& operator = (const Fix& arg)`
Assignment operator. If `*this` does not have its precision format set (i.e. it is uninitialized), the source `Fix` is copied. Otherwise, the source `Fix` value is converted to the existing precision. Either truncation or rounding takes place, based on the value of the rounding bit of the current object. Overflow results either in saturation, "zero saturation" (replacing the result with zero), or a warning error message, depending on the overflow field of the object. In these cases, `ovf_occurred` will return `TRUE` on the result.

`Fix& operator = (double arg)`
Assignment operator. The double value is first converted to a default precision `Fix` number and then assigned to `*this`.

The function of these arithmetic operators should be self-explanatory:

```
Fix& operator += (const Fix&)
Fix& operator -= (const Fix&)
Fix& operator *= (const Fix&)
Fix& operator *= (int)
Fix& operator /= (const Fix&)
Fix operator + (const Fix&, const Fix&)
Fix operator - (const Fix&, const Fix&)
Fix operator * (const Fix&, const Fix&)
Fix operator * (const Fix&, int)
Fix operator * (int, const Fix&)
Fix operator / (const Fix&, const Fix&)
Fix operator - (const Fix&) // unary minus
int operator == (const Fix& a, const Fix& b)
int operator != (const Fix& a, const Fix& b)
int operator >= (const Fix& a, const Fix& b)
int operator <= (const Fix& a, const Fix& b)
int operator > (const Fix& a, const Fix& b)
```

```
int operator < (const Fix& a, const Fix& b)
```

Note:

- These operators are designed so that overflow does not, as a rule, occur (the return value has a wider format than that of its arguments). The exception is when the result cannot be represented in a `Fix` with all 64 bits before the binary point.
- The output of any operation will have error codes that are the logical OR of those of the arguments to the operation, plus any additional errors that occurred during the operation (like divide by zero).
- The division operation is currently a cheat: it converts to double and computes the result, converting back to `Fix`.
- The relational operators ==, !=, >=, <=, >, < are all written in terms of a function
  `int compare(const Fix& a, const Fix& b)`
  This functions returns -1 if $a < b$, 0 if $a = b$, and 1 if $a > b$. The comparison is exact (every bit is checked) if the two values have the same precision format. If the precisions are different, the arguments are converted to doubles and compared. Since `double` values only have an accuracy of about 53 bits on most machines, this may cause false equality reports for `Fix` values with many bits.

Conversions:

`operator int() const`
: Return the value of the `Fix` number as an integer, truncating towards zero.

`operator float() const`

`operator double() const`
: Convert to a float or a double, creating an exact result when possible.

`void complement()`
: Replace the current value by its complement.

Fix overflow, rounding, and errors.

The `Fix` class defines the following enumerated values for overflow handling:

```
Fix::ovf_saturate

Fix::ovf_zero_saturate

Fix::ovf_wrapped

Fix::ovf_warning
```

They may be used as arguments to the `set_overflow` method, as in the following example:

```
out.set_overflow(Fix::ovf_saturate);
```

The member function

```
int overflow() const;
```

returns the overflow type. This returned result can be compared against the above enumerated values. Overflow types may also be specified as strings, using the method

```
void set_ovflow(const char* overflow_type);
```

the `overflow_type` argument may be one of `saturate`, `zero_saturate`, `wrapped`, or `warning`.

The rounding behavior of a `Fix` value may be set by calling

```
void set_rounding(int value);
```

If the argument is false, or has the value `Fix::mask_truncate`, truncation will occur. If the argument is nonzero (for example, if it has the value `Fix::mask_truncate_round`, rounding will occur. The older name `Set_MASK` is a synonym for `set_rounding`.

The following functions access the error bits of a `Fix` result:

```
int ovf_occurred() const;
int invalid() const;
int dbz() const;
```

The first function returns `TRUE` if there have been any overflows in computing the value. The second returns `TRUE` if the value is invalid, because of invalid precision parameters or a divide by zero. The third returns `TRUE` only for divide by zero.

4.3 Defining New Data Types

The Ptolemy heterogeneous message interface provides a mechanism for stars to transmit arbitrary objects to other stars. Our design satisfies the following requirements:

- Existing stars (stars that were written before the message interface was added) that handle `ANYTYPE` work with message particles without change.
- Message portholes can send different types of messages during the same simulation. This is especially useful for modeling communication networks.
- It avoids copying large messages by using a reference count mechanism, as in many C++ classes (for example, string classes).
- It is possible to safely modify large messages without excessive memory allocation and deallocation.
- It is (relatively) easy for users to define their own message types; no change to the kernel is required to support new message types.

The “message” type is understood by Ptolemy to mean a particle containing a message. There are three classes that implement the support for message types:

- The `Message` class is the base class from which all other message data types are derived. A user who wishes to define an application-specific message type derives a new class from `Message`.
- The `Envelope` class contains a pointer to an derived from `Message`. When an `Envelope` objects is copied or duplicated, the new envelope simply sets its own pointer to

the pointer contained in the original. Several envelopes can thus reference the same `Message` object. Each `Message` object contains a reference count, which tracks how many `Envelope` objects reference it; when the last reference is removed, the `Message` is deleted.

- The `MessageParticle` class is a type of `Particle` (like `IntParticle`, `FloatParticle`, etc.); it contains a `Envelope`. Ports of type "message" transmit and receive objects of this type.

Class `Particle` contains two member functions for message support: `getMessage`, to receive a message, and the `<<` operator with an `Envelope` as the right argument, to load a message into a particle. These functions return errors in the base class; they are overridden in the `MessageParticle` class with functions that perform the expected operation.

4.3.1 Defining a new Message class

Every user-defined message is derived from class `Message`. Certain virtual functions defined in that class must be overridden; others may optionally be overridden. Here is an example of a user-defined message type:

```
// This is a simple vector message object. It stores
// an array of integer values of arbitrary length.
// The length is specified by the constructor.
#include "Message.h"
class IntVecData: public Message {
private:
      int len;
      init(int length,int *srcData) {
            len = length;
            data = new int[len];
            for (int i = 0; i < len; i++)
                  data[i] = *srcData++;
      }
public:
      // the pointer is public for simplicity
      int *data;

      int length() const { return len;}

      // functions for type-checking
      const char* dataType() const { return "IntVecData";}
      // isA responds TRUE if given the name of the class or
      // of any baseclass.
      int isA(const char* typ) const {
            if (strcmp(typ,"IntVecData") == 0) return TRUE;
            else return Message::isA(typ);
      }
      // constructor: makes an uninitialized array
      IntVecData(int length): len(length) {
            data = new int[length];
      }
      // constructor: makes an initialized array from a int array
      IntVecData(int length,int *srcData) { init(length,srcData);}
```

```
        // copy constructor
        IntVecData(const IntVecData& src) { init(src.len,src.data);}

        // clone: make a duplicate object
        Message* clone() const { return new IntVecData(*this);}

        // destructor
        ~IntVecData() {
              delete data;
        }
};
```

This message object can contain a vector of integers of arbitrary length. Some functions in the class are arbitrary and the user may define them in whatever way is most convenient; however, there are some requirements.

The class must redefine the `dataType` method from class `Message`. This function returns a string identifying the message type. This string should be identical to the name of the class. In addition, the `isA` method must be defined. The `isA` method responds with `TRUE` (1) if given the name of the class or of any base class; it returns `FALSE` (0) otherwise. This mechanism permits stars to handle any of a whole group of message types, even for classes that are defined after the star is written.

Because of the regular structure of `isA` function bodies, macros are provided to generate them. The `ISA_INLINE` macro expands to an inline definition of the function; for example,

```
ISA_INLINE(IntVecData,Message)
```

could have been written above instead of the definition of `isA` to generate exactly the same code. Alternatively, to put the function body in a `.cc` file, one can write

```
int isA(const char*) const;
```

in the class definition and put

```
ISA_FUNC(IntVecData,Message)
```

in the `.cc` file (or wherever the methods are defined).

The class must define a copy constructor, unless the default copy constructor generated by the compiler, which does memberwise copying, will do the job.

The class must redefine the `clone` method of class `Message`. Given that the copy constructor is defined, the form shown in the example, where a new object is created with the `new` operator and the copy constructor, will suffice.

In addition, the user may optionally define type conversion and printing functions if they make sense. If a star that produces messages is connected to a star that expects integers (or floating values, or complex values), the appropriate type conversion function is called. The base class, `Message`, defines the virtual conversion functions `asInt()`, `asFloat()`, and `asComplex()` and the printing method `print()` — see the file `$PTOLEMY/src/kernel/Message.h` for their exact types. The base class conversion functions assert a run-time error, and the default print function returns a `StringList` saying

<*type*>: no print method

where *type* is whatever is returned by `dataType()`.

By redefining these methods, you can make it legal to connect a star that generates messages to a star that expects integer, floating, or complex particles, or you can connect to a `Printer` or `XMgraph` star (for `XMgraph` to work, you must define the `asFloat` function; for `Printer` to work, you must define the `print` method).

4.3.2 Use of the Envelope class

The `Envelope` class references objects of class `Message` or derived classes. Once a message object is placed into an envelope object, the envelope takes over responsibility for managing its memory: maintaining reference counts, and deleting the message when it is no longer needed.

The constructor (which takes as its argument a reference to a `Message`), copy constructor, assignment operator, and destructor of `Envelope` manipulate the reference counts of the references `Message` object. Assignment simply copies a pointer and increments the reference count. When the destructor of a `Envelope` is called, the reference count of the `Message` object is decremented; if it becomes zero, the `Message` object is deleted. Because of this deletion, a `Message` must never be put inside a `Envelope` unless it was created with the `new` operator. Once a `Message` object is put into an `Envelope` it must never be explicitly deleted; it will "live" as long as there is at least one `Envelope` that contains it, and it will then be deleted automatically.

It is possible for an `Envelope` to be "empty". If it is, the `empty` method will return `TRUE`, and the data field will point to a special "dummy message" with type `DUMMY` that has no data in it.

The `dataType` method of `Envelope` returns the datatype of the contained `Message` object; the methods `asInt()`, `asFloat()`, `asComplex()`, and `print()` are also "passed through" in a similar way to the contained object.

Two `Envelope` methods are provided for convenience to make type checking simpler: `typeCheck` and `typeError`. A simple example illustrates their use:

```
if (!envelope.typeCheck("IntVecData")) {
      Error::abortRun(*this, envelope.typeError("IntVecData"));
      return;
}
```

The method `typeCheck` calls `isA` on the message contents and returns the result, so an error will be reported if the message contents are not `IntVecData` and are not derived from `IntVecData`. Since the above code segment is so common in stars; a macro is included in `Message.h` to generate it; the macro

```
TYPE_CHECK(envelope,"IntVecData");
```

expands to essentially the same code as above. The `typeError` method generates an appropriate error message:

```
Expected message type 'arg', got 'type'
```

To access the data, two methods are provided: `myData()` and `writableCopy()`. The `myData` function returns a pointer to the contained `Message`-derived object. *The data pointed*

to by this pointer must not be modified, since other `Envelope` objects in the program may also contain it. If you convert its type, always make sure that the converted type is a pointer to `const` (see the programming example for `UnPackInt` below). This ensures that the compiler will complain if you do anything illegal.

The `writableCopy` function also returns a pointer to the contained object, but with a difference. If the reference count is one, the envelope is emptied (set to the dummy message) and the contents are returned. If the reference count is greater than one, a *clone* of the contents is made (by calling its `clone()` function) and returned; again the envelope is zeroed (to prevent the making of additional clones later on).

In some cases, a star writer will need to keep a received `Message` object around between executions. The best way to do this is to have the star contain a member of type `Envelope`, and to use this member object to hold the message data between executions. Messages should always be kept in envelopes so that the user does not have to worry about managing their memory.

4.3.3 Use of the MessageParticle class

If a porthole is of type "message", then its particles are objects of the class `MessageParticle`. A `MessageParticle` is simply a particle whose data field is an `Envelope`, which means that it can hold a `Message` in the same way that `Envelope` objects do.

Many methods of the `Particle` class are redefined in the `MessageParticle` class to cause a run-time error; for example, it is illegal to send an integer, floating, or complex number to the particle with the `<<` operator. The conversion operators (conversion to type `int`, `double`, or `Complex`) return errors by default, but can be made legal by redefining the `asInt`, `asFloat`, or `asComplex` methods for a specific message type.

The principal operations on `MessageParticle` objects are `<<` with an argument of type `Envelope`, to load a message into the particle, and `getMessage(Envelope&)`, to transfer message contents from the particle into a user-supplied message. The `getMessage` method removes the message contents from the particle[1]. In cases where the destructive behavior of `getMessage` cannot be tolerated, an alternative interface, `accessMessage(Envelope&)`, is provided. It does not remove the message contents from the particle. Promiscuous use of `accessMessage` in systems where large-sized messages may be present can cause the amount of virtual memory occupied to grow (though all message will be deleted eventually).

4.3.4 Use of messages in stars

Here are a couple of simple examples of stars that produce and consume messages. For more advanced samples, look in the Ptolemy distribution for stars that produce or consume messages. The image processing classes and stars, which are briefly described below in "Image particles" on page 4-40, provide a particularly rich set of examples. The matrix classes described on page 4-21 are also good examples. The matrix classes are recognized in the Ptolemy kernel, and supported by `pigi` and `ptlang`.

1. The reason for this "aggressive reclamation" policy (both here and in other places) is to minimize the number of no-longer-needed messages in the system and to prevent unnecessary clones from being generated by writableCopy() by eliminating references to Message objects as soon as possible.

```
defstar {
	name { PackInt }
	domain { SDF }
	desc { Accept integer inputs and produce IntVecData messages.}
	defstate {
		name { length }
		type { int }
		default { 10 }
		desc { number of values per message }
	}
	input {
		name { input }
		type { int }
	}
	output {
		name { output }
		type { message }
	}
	ccinclude { "Message.h", "IntVecData.h" }
	start {
		input.setSDFParams(int(length),int(length-1));
	}
	go {
		int l = length;
		IntVecData * pd = new IntVecData(l);
		// Fill in message. input%0 is newest, must reverse
		for (int i = 0; i < l; i++)
			pd->data[l-i-1] = int(input%i);
		Envelope pkt(*pd);
		output%0 << pkt;
	}
}
```

Since this is an SDF star, it must produce and consume a constant number of tokens on each step, so the message length must be fixed (though it is controllable with a state). See “Setting SDF porthole parameters” on page 7-1 for an explanation of the `setSDFParams` method. Notice that the output porthole is declared to be of type `message`. Notice also the `ccinclude` statement; we must include the file `Message.h` in all message-manipulating stars, and we must also include the definition of the specific message type we wish to use.

The code itself is fairly straightforward—an `IntVecData` object is created with `new`, is filled in with data, and is put into an `Envelope` and sent. Resist the temptation to declare the `IntVecData` object as a local variable: it will not work. It must reside on the heap. Here is a star to do the inverse operation:

```
defstar {
	name { UnPackInt }
	domain { SDF }
	desc {
Accept IntVecData messages and produce integers. The first 'length'
values from each message are produced.
```

```
        }
        defstate {
              name { length }
              type { int }
              default { 10 }
              desc { number of values output per message }
        }
        input {
              name { input }
              type { message }
        }
        output {
              name { output }
              type { int }
        }
        ccinclude { "Message.h", "IntVecData.h" }
        start {
              output.setSDFParams(int(length),int(length-1));
        }
        go {
              Envelope pkt;
              (input%0).getMessage(pkt);
              if (!pkt.typeCheck("IntVecData")) {
                    Error::abortRun(*this,pkt.typeError("IntVecData"));
                    return;
              }
              const IntVecData * pd = (const IntVecData *)pkt.myData();
              if (pd.length() < int(length)) {
                    Error::abortRun(*this,
                          "Received message is too short");
                    return;
              }
              for (i = 0; i < int(length); i++) {
                    output%(int(length)-i-1) << pd->data[i];
              }
        }
}
```

Because the domain is SDF, we must always produce the same number of outputs regardless of the size of the messages. The simple approach taken here is to require at least a certain amount of data or else to trigger an error and abort the run.

The operations here are to declare an envelope, get the data from the particle into the envelope with `getMessage`, check the type, and then access the contents. Notice the cast operation; this is needed because `myData` returns a const pointer to class `Message`. It is important that we converted the pointer to `const IntVecData *` and not `IntVecData*` because we have no right to modify the message through this pointer. Many C++ compilers will not warn by default about “casting away const”; we recommend turning on compiler warnings when compiling code that uses messages to avoid getting into trouble (for g++, say `-Wcast-qual`; for *cfront*-derived compilers, say `+w`**)**.

If we wished to modify the message and then send the result as an output, we would call `writableCopy` instead of `myData`, modify the object, then send it on its way as in the

previous star.

4.4 The Matrix Data Types

The primary support for matrix types in Ptolemy is the `PtMatrix` class. `PtMatrix` is derived from the `Message` class, and uses the various kernel support functions for working with the `Message` data type as described in Section 4.3 on page 4-14. This section discusses the `PtMatrix` class and how to write stars and programs using this class.

4.4.1 Design philosophy

The `PtMatrix` class implements two dimensional arrays. There are four key classes derived from `PtMatrix`: `ComplexMatrix`, `FixMatrix`, `FloatMatrix`, and `IntMatrix`. (Note that `FloatMatrix` is a matrix of C++ `doubles`.) A review of matrix classes implemented by other programmers revealed two main styles of implementation: a vector of vectors, or a simple array. In addition, there are two main formats of storing the entries: column-major ordering, where all the entries in the first column are stored before the entries of the second column, and row-major ordering, where the entries are stored starting with the first row. Column-major ordering is how Fortran stores arrays whereas row-major ordering is how C stores arrays.

The Ptolemy `PtMatrix` class stores data as a simple C array, and therefore uses row-major ordering. Row-major ordering also seems more natural for operations such as image and video processing, but it might make it more difficult to interface Ptolemy's `PtMatrix` class with Fortran library calls. The limits of interfacing Ptolemy's `PtMatrix` class with other software is discussed in Section 4.4.5 on page 4-33.

The design decision to store data entries in a C array rather than as an array of vector objects has a greater effect on performance than the decision whether to use row major or column major ordering. There are a couple of advantages to implementing a matrix class as an array of vector class objects: referencing an entry may be faster, and it is easier to do operations on a whole row or column of the matrix, depending on whether the format is an array of column vectors or an array of row vectors. An entry lookup in an array of row vectors requires two index lookups: one to find the desired row vector in the array and one to find the desired entry of that row. A linear array, in contrast, requires a multiplication to find the location of first element of the desired row and then an index lookup to find the column in that row. For example, `A[row][col]` is equivalent to looking up `&data + (row*numRows + col)` if the entries are stored in a C array `data[]`, whereas it is `*(&rowArray + row) + col` if looking up the entry in an array of vectors format.

Although the array of vectors format has faster lookups, it is also more expensive to create and delete the matrix. Each vector of the array must be created in the matrix constructor, and each vector must also be deleted by the matrix destructor. The array of vectors format also requires more memory to store the data and the extra array of vectors.

With the advantages and disadvantages of the two systems in mind, we chose to implement the `PtMatrix` class with the data stored in a standard C array. Ptolemy's environment is such that matrices are created and deleted constantly as needed by stars: this negates much of the speedup gained from faster lookups. Also, we felt it was important to keep the design of the class simple and the memory usage efficient because of Ptolemy's increasing size and

complexity.

4.4.2 The PtMatrix class

The PtMatrix base class is derived from the Message class so that we can use Ptolemy's Envelope class and message-handling system. However, the MessageParticle class is not used by the PtMatrix class; instead, there are special MatrixEnvParticle classes defined to handle type checking between the various types of matrices. This allows the system to automatically detect when two stars with different matrix type inputs and outputs are incorrectly connected together.[1] Also, the MatrixEnvParticle class has some special functions not found in the standard MessageParticle class to allow easier handling of PtMatrix class messages. A discussion of how to pass PtMatrix class objects using the MatrixEnvParticles can be found in a following section.

As explained previously, there are currently four data-specific matrix classes: ComplexMatrix, FixMatrix, FloatMatrix, and IntMatrix. Each of these classes stores its entries in a standard C array named data, which is an array of data objects corresponding to the PtMatrix type: Complex, Fix, double, or int. These four matrix classes implement a common set of operators and functions; in addition, the ComplexMatrix class has a few special methods such as conjugate() and hermitian() and the FixMatrix class has a number of special constructors that allow the user to specify the precision of the entries in the matrix. Generally, all entries of a FixMatrix will have the same precision.

The matrix classes were designed to take full advantage of operator overloading in C++ so that operations on matrix objects can be written much like operations on scalar ones. For example, the two-operand multiply operator * has been defined so that if A and B are matrices, A * B will return a third matrix that is the matrix product of A and B.

4.4.3 Public functions and operators for the PtMatrix class

The functions and operators listed below are implemented by all matrix classes (ComplexMatrix, FixMatrix, FloatMatrix, and IntMatrix) unless otherwise noted. The symbols used are:

- XXX refers to one of the following: Complex, Fix, Float, or Int
- xxx refers to one of the following: Complex, Fix, double, or int

Functions and Operators to access entries of the Matrix:

`xxx& entry(int i)`

Example: A.entry(i)

Return the i^{th} entry of the matrix when its data storage is considered to be a linear array. This is useful for quick operations on every entry of the matrix without regard for the specific (row,column) position of that entry. The total number of entries in the matrix is defined to be numRows() * numCols(), with indices ranging from 0 to num-

1. We recommend, however, that you do not adapt this method to your own types, but use the standard method of adding new message types described in Section 4.3. The method currently used for the matrix classes may not be supported in future releases.

`Rows() * numCols() - 1`. This function returns a reference to the actual entry in the matrix so that assignments can be made to that entry. In general, functions that wish to linearly reference each entry of a matrix `A` should use this function instead of the expression `A.data[i]` because classes which are derived from `PtMatrix` can then overload the `entry()` method and reuse the same functions.

`xxx* operator [] (int row)`

Example: `A[row][column]`

Return a pointer to the start of the row in the matrix's data storage. (This operation is different to matrix classes defined as arrays of vectors, in which the `[]` operator returns the vector representing the desired row.) This operator is generally not used alone but with the `[]` operator defined on C arrays, so that `A[i][j]` will give you the entry of the matrix in the i^{th} row and j^{th} column of the data storage. The range of rows is from 0 to `numRows()-1` and the range of columns is from 0 to `numCols()-1`.

Constructors:

`XXXMatrix()`

Example: `IntMatrix A;`

Create an uninitialized matrix. The number of rows and columns are set to zero and no memory is allocated for the storage of data.

`XXXMatrix(int numRow, int numCol)`

Example: `FloatMatrix A(3,2);`

Create a matrix with dimensions `numRow` by `numCol`. Memory is allocated for the data storage but the entries are uninitialized.

`XXXMatrix(int numRow, int numCol, PortHole& p)`

Example: `ComplexMatrix(3,3,myPortHole)`

Create a matrix of the given dimensions and initialize the entries by assigning to them values taken from the porthole `myPortHole`. The entries are assigned in a rasterized sequence so that the value of the first particle removed from the porthole is assigned to entry (0,0), the second particle's value to entry (0,1), etc. It is assumed that the porthole has enough particles in its buffer to fill all the entries of the new matrix.

`XXXMatrix(int numRow, int numCol, XXXArrayState& dataArray)`

Example: `IntMatrix A(2,2,myIntArrayState);`

Create a matrix with the given dimensions and initialize the entries to the values in the given `ArrayState`. The values of the `ArrayState` fill the matrix in rasterized sequence so that entry (0,0) of the matrix is the first entry of the `ArrayState`, entry (0,1) of the matrix is the second, etc. An error is generated if the `ArrayState` does not have enough values to initialize the whole matrix.

`XXXMatrix(const XXXMatrix& src)`

Example: `FixMatrix A(B);`
This is the copy constructor. A new matrix is formed with the same dimensions as the source matrix and the data values are copied from the source.

`XXXMatrix(const XXXMatrix& src, int startRow, int startCol, int numRow, int numCol)`
Example: `IntMatrix A(B,2,2,3,3);`
This special "submatrix" constructor creates a new matrix whose values come from a submatrix of the source. The arguments `startRow` and `startCols` specify the starting row and column of the source matrix. The values `numRow` and `numCol` specify the dimensions of the new matrix. The sum `startRow + numRow` must not be greater than the maximum number of rows in the source matrix; similarly, `startCol + numCol` must not be greater than the maximum number of columns in the source. For example, if `B` is a matrix with dimension (4,4), then `A(B,1,1,2,2)` would create a new matrix `A` that is a (2,2) matrix with data values from the center quadrant of matrix `B`, so that `A[0][0] == B[1][1]`, `A[0][1] == B[1][2]`, `A[1][0] == B[2][1]`, and `A[1][1] == B[2][2]`.

The following are special constructors for the `FixMatrix` class that allow the programmer to specify the precision of the entries of the `FixMatrix`.

`FixMatrix(int numRow, int numCol, int length, int intBits)`
Example: `FixMatrix A(2,2,14,4);`
Create a `FixMatrix` with the given dimensions such that each entry is a fixed-point number with precision as given by the `length` and `intBits` inputs.

`FixMatrix(int numRow, int numCol, int length, int intBits, PortHole& myPortHole)`
Example: `FixMatrix A(2,2,14,4);`
Create a `FixMatrix` with the given dimensions such that each entry is a fixed-point number with precision as given by the `length` and `intBits` inputs and initialized with the values that are read from the particles contained in the porthole `myPortHole`.

`FixMatrix(int numRow, int numCol, int length, int intBits, FixArrayState& dataArray)`
Example: `FixMatrix A(2,2,14,4);`
Create a `FixMatrix` with the given dimensions such that each entry is a fixed-point number with precision as given by the `length` and `intBits` inputs and initialized with the values in the given `FixArrayState`.

There are also special copy constructors for the `FixMatrix` class that allow the programmer to specify the precision of the entries of the `FixMatrix` as they are copied from the sources. These copy constructors are usually used for easy conversion between the other matrix types.

The last argument specifies the type of masking function (truncate, rounding, etc.) to be used when doing the conversion.

`FixMatrix(const XXXMatrix& src, int length, int intBits, int round)`
Example: `FixMatrix A(CxMatrix,4,14,TRUE);`
Create a `FixMatrix` with the given dimensions such that each entry is a fixed-point number with precision as given by the `length` and `intBits` arguments. Each entry of the new matrix is copied from the corresponding entry of the src matrix and converted as specified by the `round` argument.

Comparison operators:

`int operator == (const XXXMatrix& src)`
Example: `if(A == B) then` ...
Return `TRUE` if the two matrices have the same dimensions and every entry in `A` is equal to the corresponding entry in `B`. Return `FALSE` otherwise.

`int operator != (const XXXMatrix& src)`
Example: `if(A != B) then` ...
Return `TRUE` if the two matrices have different dimensions or if any entry of `A` differs from the corresponding entry in `B`. Return `FALSE` otherwise.

Conversion operators:

Each matrix class has a conversion operator so that the programmer can explicitly cast one type of matrix to another (this casting is done by copying). It would have been possible to make conversions occur automatically when needed, but because these conversions can be quite expensive for large matrices, and because unexpected results might occur if the user did not intend for a conversion to occur, we chose to require that these conversions be used explicitly.

`operator XXXMatrix () const`
Example: `FloatMatrix C = A * (FloatMatrix)B;`
Convert a matrix of one type into another. These conversions allow the various arithmetic operators, such as `*` and `+`, to be used on matrices of different type. For example, if `A` in the example above is a (3,3) `FloatMatrix` and `B` is a (3,2) `IntMatrix`, then `C` is a `FloatMatrix` with dimensions (3,2).

Destructive replacement operators:

These operators are member functions that modify the current value of the object. In the following examples, `A` is usually the lvalue (`*this`). All operators return `*this`:

`XXXMatrix& operator = (const XXXMatrix& src)`
Example: `A = B;`

This is the assignment operator: make `A` into a matrix that is a copy of `B`. If `A` already has allocated data storage, then the size of this data storage is compared to the size of `B`. If they are equal, then the dimensions of `A` are simply set to those of `B` and the entries copied. If they are not equal, the data storage is freed and reallocated before copying.

`XXXMatrix& operator = (xxx value)`
Example: `A = value;`
Assign each entry of `A` to have the given `value`. Memory management is handled as in the previous operator.
Note: this operator is targeted for deletion. Do not use it.

`XXXMatrix& operator += (const XXXMatrix& src)`
Example: `A += B;`
Perform the operation `A.entry(i) += B.entry(i)` for each entry in `A`. `A` and `B` must have the same dimensions.

`XXXMatrix& operator += (xxx value)`
Example: `A += value;`
Add the scalar `value` to each entry in the matrix.

`XXXMatrix& operator -= (const XXXMatrix& src)`
Example: `A -= B;`
Perform the operation `A.entry(i) -= B.entry(i)` for each entry in `A`. `A` and `B` must have the same dimensions.

`XXXMatrix& operator -= (xxx value)`
Example: `A -= value;`
Subtract the scalar `value` from each entry in the matrix.

`XXXMatrix& operator *= (const XXXMatrix& src)`
Example: `A *= B;`
Perform the operation `A.entry(i) *= B.entry(i)` for each entry in `A`. `A` and `B` must have the same dimensions. Note: this is an elementwise operation and is *not* equivalent to A = A * B.

`XXXMatrix& operator *= (xxx value)`
Example: `A *= value;`
Multiply each entry of the matrix by the scalar `value`.

`XXXMatrix& operator /= (const XXXMatrix& src)`
Example: `A /= B;`
Perform the operation `A.entry(i) /= B.entry(i)` for each entry in `A`. `A` and `B` must have the same dimensions.

`XXXMatrix& operator /= (xxx value)`
`Example: A /= value`
Divide each entry of the matrix by the scalar `value`. The scalar value must be non-zero.

`XXXMatrix& operator identity()`
Example: `A.identity();`
Change `A` to be an identity matrix so that each entry on the diagonal is 1 and all off-diagonal entries are 0.

Non-destructive operators (these return a new matrix):

`XXXMatrix operator - ()`
Example: `B = -A;`
Return a new matrix such that each element is the negative of the element of the source.

`XXXMatrix operator ~ ()`
Example: `B = ~A;`
Return a new matrix that is the transpose of the source.

`XXXMatrix operator ! ()`
Example: `B = !A;`
Return a new matrix which is the inverse of the source.

`XXXMatrix operator ^ (int exponent)`
Example: `B = A^2;`
Return a new matrix which is the source matrix to the given `exponent` power. The `exponent` can be negative, in which case the `exponent` is first treated as a positive number and the final result is then inverted. So `A^2 == A*A` and `A^(-3) == !(A*A*A)`.

`XXXMatrix transpose()`
Example: `B = A.transpose();`
This is the same as the `~ operator` but called by a function name instead of as an operator.

`XXXMatrix inverse()`
Example: `B = A.inverse();`
This is the same as the `! operator` but called by a function name instead of as an operator.

`ComplexMatrix conjugate()`
Example: `ComplexMatrix B = A.conjugate();`
Return a new matrix such that each element is the complex conjugate of the source. This function is defined for the `ComplexMatrix` class only.

`ComplexMatrix hermitian()`
Example: `ComplexMatrix B = A.hermitian();`
Return a new matrix which is the Hermitian Transpose (conjugate transpose) of the source. This function is defined for the `ComplexMatrix` class only.

Non-member binary operators:

`XXXMatrix operator + (const XXXMatrix& left, const XXXMatrix& right)`
Example: `A = B + C;`
Return a new matrix which is the sum of the first two. The `left` and `right` source matrices must have the same dimensions.

`XXXMatrix operator + (const xxx& scalar, const XXXMatrix& matrix)`
Example: `A = 5 + B;`
Return a new matrix that has entries of the `source` matrix added to a `scalar` value.

`XXXMatrix operator + (const XXXMatrix& matrix, const xxx& scalar)`
Example: `A = B + 5;`
Return a new matrix that has entries of the source matrix added to a scalar value. (This is the same as the previous operator but with the `scalar` on the right.)

`XXXMatrix operator - (const XXXMatrix& left, const XXXMatrix& right)`
Example: `A = B - C;`
Return a new matrix which is the difference of the first two. The `left` and `right` source matrices must have the same dimensions.

`XXXMatrix operator - (const xxx& scalar, const XXXMatrix& matrix)`
Example: `A = 5 - B;`
Return a new matrix that has the negative of the entries of the source `matrix` added to a `scalar` value.

`XXXMatrix operator - (const XXXMatrix& matrix, const xxx& scalar)`
Example: `A = B - 5;`
Return a new matrix such that each entry is the corresponding entry of the source `matrix` minus the `scalar` value.

`XXXMatrix operator * (const XXXMatrix& left, const XXXMatrix& right)`
Example: `A = B * C;`
Return a new matrix which is the matrix product of the first two. The `left` and `right` source matrices must have compatible dimensions (i.e. `A.numCols() == B.numRows()`.

`XXXMatrix operator * (const xxx& scalar, const XXXMatrix& matrix)`
Example: `A = 5 * B;`

Return a new matrix that has entries of the source `matrix` multiplied by a `scalar` value.

`XXXMatrix operator * (const XXXMatrix& matrix, const xxx& scalar)`
Example: `A = B * 5;`
Return a new matrix that has entries of the source matrix multiplied by a scalar value. (This is the same as the previous operator but with the `scalar` on the right.)

Miscellaneous functions:

`int numRows()`
Return the number of rows in the matrix.

`int numCols()`
Return the number of columns in the matrix.

`Message* clone()`
Example: `IntMatrix *B = A.clone();`
Return a copy of `*this`.

`StringList print()`
Example: `A.print()`
Return a formatted `StringList` that can be printed to display the contents of the matrix in a reasonable format.

`XXXMatrix& multiply (const XXXMatrix& left, const XXXMatrix& right, XXXMatrix& result)`
Example: `multiply(A,B,C);`
This is a faster 3 operand form of matrix multiply such that the result matrix is passed as an argument so that we avoid the extra copy step that is involved when we write `C = A * B`.

`const char* dataType()`
Example: `A.dataType()`
Return a string that specifies the name of the type of matrix. The strings are "`ComplexMatrix`", "`FixMatrix`", "`FloatMatrix`", and "`IntMatrix`".

`int isA(const char* type)`
Example: `if(A.isA("FixMatrix")) then ...`
Return `TRUE` if the argument string matches the type string of the matrix.

4.4.4 Writing stars and programs using the PtMatrix class

This section describes how to use the matrix data classes when writing stars. Some examples will be given here but the programmer should refer to the stars in `$PTOLEMY/src/domains/sdf/matrix/stars/*.pl` and `$PTOLEMY/src/domains/sdf/image/`

`stars/*.pl` for more examples

Memory management

The most important thing to understand about the use of matrix data classes in the Ptolemy environment is that stars that intend to output the matrix in a particle should allocate memory for the matrix *but never delete that matrix*. Memory reclamation is done automatically by the reference-counting mechanism of the `Message` class. Strange errors will occur if the star deletes the matrix before it is used by another star later in the execution sequence.

Naming conventions

Stars that implement general-purpose matrix operations usually have names with the `_M` suffix to distinguish them from stars that operate on scalar particles. For example, the `SDFGain_M` star multiplies an input matrix by a scalar value and outputs the resulting matrix. This is in contrast to `SDFGain`, which multiplies an input value held in a `FloatParticle` by a double and puts that result in an output `FloatParticle`.

Include files

For a star to use the `PtMatrix` classes, it must include the file `Matrix.h` in either its `.h` or `.cc` file. If the star has a matrix data member, then the declaration

```
hinclude { "Matrix.h" }
```

needs to be in the `Star` definition. Otherwise, the declaration

```
ccinclude { "Matrix.h" }
```

is sufficient.

To declare an input porthole that accepts matrices, the following syntax is used:

```
input {
      name { inputPortHole }
      type { FLOAT_MATRIX_ENV }
}
```

The syntax is the same for output portholes. The type field can be `COMPLEX_MATRIX_ENV`, `FLOAT_MATRIX_ENV`, `FIX_MATRIX_ENV`, or `INT_MATRIX_ENV`. The icons created by Ptolemy will have terminals that are thicker and that have larger arrow points than the terminals for scalar particle types. The colors of the terminals follow the pattern of colors for scalar data types (e.g., blue represents `Float` and `FloatMatrix`).

Input portholes

The syntax to extract a matrix from the input porthole is:

```
Envelope inPkt;
(inputPortHole%0).getMessage(inPkt);
const FloatMatrix& inputMatrix =
      *(const FloatMatrix *)inPkt.myData();
```

The first line declares an `Envelope`, which is used to access the matrix. Details of the `Envelope` class are given in “Use of the Envelope class” on page 4-17. The second line fills the envelope with the input matrix. Note that, because of the reference-counting mechanism, this line does not make a copy of the matrix. The last two lines extract a reference to the matrix

from the envelope. It is up to the programmer to make sure that the cast agrees with the definition of the input port.

Because multiple envelopes might reference the same matrix, a star is generally not permitted to modify the matrix held by the `Envelope`. Thus, the function `myData()` returns a `const Message *`. We cast that to be a `const FloatMatrix *` and then de-reference it and assign the value to `inputMatrix`. It is generally better to handle matrices by reference instead of by pointer because it is clearer to write "`A + B`" rather than "`*A + *B`" when working with matrix operations. Stars that wish to modify an input matrix should access it using the `writableCopy` method, as explained in "Use of the Envelope class" on page 4-17.

Allowing delays on inputs

The cast to `(const FloatMatrix *)` above is not always safe. Even if the source star is known to provide matrices of the appropriate type, a delay on the arc connecting the two stars can cause problems. In particular, delays in dataflow domains are implemented as initial particles on the arcs. These initial particles are given the value "zero" as defined by the type of particle. For `Message` particles, a "zero" is an uninitialized `Message` particle containing a "dummy" data value. This dummy `Message` will be returned by the `myData` method in the third line of the above code fragment. The dummy message is not a `FloatMatrix`, rendering the above cast invalid. A star that expects matrix inputs must have code to handle empty particles. An example is:

```
if(inPkt.empty()) {
      FloatMatrix& result = *(new FloatMatrix(int(numRows),
                                    int(numCols)));
      result = 0.0;
      output%0 << result;
}
```

There are many ways that an empty input can be interpreted by a star that operates on matrices. For example, a star multiplying two matrices can simply output a zero matrix if either input is empty. A star adding two matrices can output whichever input is not empty. Note above that we create an output matrix that has the dimensions as set by the state parameters of the star so that any star that uses this output will have valid data.

A possible alternative to outputting a zero matrix is to simply pass that empty `MessageParticle` along. This approach, however, can lead to counterintuitive results. Suppose that empty message reaches a display star like `TkText`, which will attempt to call the `print()` method of the object. An empty message has a `print()` method that results in a message like

<*type*>: no print method

This is likely to prove extremely confusing to users, so we strongly recommend that each matrix star handle the empty input in a reasonable way, and produce a non-empty output.

Matrix outputs

To put a matrix into an output porthole, the syntax is:

```
FloatMatrix& outMatrix =*(new FloatMatrix(someRow,someCol));
```

```
                // ... do some operations on the outMatrix
    outputPortHole%0 << outMatrix;
```

The last line is similar to outputting a scalar value. This is because we have overloaded the << operator for MatrixEnvParticles to support PtMatrix class inputs. The standard use of the MessageParticle class requires you to put your message into an envelope first and then use << on the envelope (see “Use of the Envelope class” on page 4-17), but we have specialized this so that the extra operation of creating an envelope first is not explicit.

Here is an example of a complete star definition that inputs and outputs matrices:

```
defstar {
      name { Mpy_M }
      domain { SDF }
      desc {
Does a matrix multiplication of two input Float matrices A and B to
produce matrix C.
      Matrix A has dimensions (numRows,X).
      Matrix B has dimensions (X,numCols).
      Matrix C has dimensions (numRows,numCols).
The user need only specify numRows and numCols. An error will be
generated automatically if the number of columns in A does not match
the number of columns in B.
      }
      input {
            name { Ainput }
            type { FLOAT_MATRIX_ENV }
      }
      input {
            name { Binput }
            type { FLOAT_MATRIX_ENV }
      }
      output {
            name { output }
            type { FLOAT_MATRIX_ENV }
      }
      defstate {
            name { numRows }
            type { int }
            default { 2 }
            desc { The number of rows in Matrix A and Matrix C.}
      }
      defstate {
            name { numCols }
            type { int }
            default { 2 }
            desc { The number of columns in Matrix B and Matrix C}
      }
      ccinclude { "Matrix.h" }
      go {
            // get inputs
            Envelope Apkt;
            (Ainput%0).getMessage(Apkt);
            const FloatMatrix& Amatrix =
```

```
                        *(const FloatMatrix *)Apkt.myData();

                    Envelope Bpkt;
                    (Binput%0).getMessage(Bpkt);
                    const FloatMatrix& Bmatrix =
                        *(const FloatMatrix *)Bpkt.myData();

                    // check for "null" matrix inputs, which could be
                    // caused by delays on the input line
                    if(Apkt.empty() || Bpkt.empty()) {
                        // if either input is empty, return a zero
                        // matrix with the state dimensions
                        FloatMatrix& result =
                            *(new FloatMatrix(int(numRows),
                                    int(numCols)));
                        result = 0.0;
                        output%0 << result;
                    }
                    else {
                        // Amatrix and Bmatrix are both valid
                        if((Amatrix.numRows() != int(numRows)) ||
                            (Bmatrix.numCols() != int(numCols))) {
                            Error::abortRun(*this,
                            "Dimension size of FloatMatrix inputs do ",
                            "not match the given state parameters.");
                            return;
                        }
                        // do matrix multiplication
                        FloatMatrix& result =
                            *(new FloatMatrix(int(numRows),
                                    int(numCols)));
                        // we could write
                        //    result = Amatrix * Bmatrix;
                        // but the following is faster
                        multiply(Amatrix,Bmatrix,result);

                        output%0 << result;
                    }
                }
            }
```

4.4.5 Future extensions

After reviewing the libraries of numerical analysis software that is freely available on the Internet, it is clear that it would be beneficial to extend the `PtMatrix` class by adding those well-tested libraries as callable functions. Unfortunately, many of those libraries are currently only available in Fortran, and there are some incompatibilities with Fortran's column major ordering and C's row major ordering. Those problems would still exist even if the Fortran code was converted to C. There are a few groups which are currently working on C++ ports of the numerical analysis libraries. One notable group is the Lapack++[1] project which is

1. **LAPACK++: A Design Overview of Object-Oriented Extensions for High Performance Linear Algebra**, by Jack J. Dongarra, Roldan Pozo, and David W. Walker, available on *netlib.*

developing a flexible matrix class of their own, besides porting the Fortran algorithms of Lapack into C++. This might possibly be incorporated in a future release.

4.5 The File and String Types

There are two experimental types in Ptolemy that support non-numeric computation. These types represent the beginnings of an effort to extend Ptolemy's dataflow model to "non-dataflow" problems such as scheduling and design flow. Their interfaces are still being developed, so should be expected to change in future releases. We would welcome suggestions on how to improve the interface and functionality of these two types.

4.5.1 The File type

The file type is implemented by the classes `FileMessage` and `FileParticle`, which are derived from `Message` and `Particle`. It uses the reference-counting mechanism of the `Message` and `Envelope` classes to ensure that files are not deleted until no longer needed. Although we created a new particle type to allow these types to appear in the `pigi` graphical interface, we recommend that you use the `Message` interface described in Section 4.3 for your own types.

The `File` type adds the following functions to `Message`:

Constructors

`FileMessage()`
: Create a new file message with a unique filename. By default, the file will be deleted when no file messages reference it.

`FileMessage(const char* name)`
: Create a new file message with the given filename. By default, the file will not be deleted when no file messages reference it.

`FileMessage(const FileMessage& src)`
: Create a new file message containing the same filename as the given file message. By default, the file will not be deleted when no file messages reference it.

Operations

`const char* fileName()`
: Return the file name contained in this message.

`StringList print()`
: Return the file name contained in this message in a `StringList` object.

`const char* fileName()`
: Return the file name contained in this message.

`void setTransient(int transient)`
: Set the status of the file. If transient is `TRUE`, the file will be deleted

when no file messages reference it; if FALSE, then it will not be deleted.

4.5.2 The String type

The string type is implemented by the classes StringMessage and StringParticle, which are derived from Message and Particle. It contains an InfString object—InfString is a version of StringList that allows limited modification, and is used to interface C++ to Tcl. Again, It uses the reference-counting mechanism of the Message and Envelope classes to ensure that strings are not deleted until no longer needed. StringMessage is currently very simple—it adds the following functions to Message:

Constructors

`StringMessage()`
: Create a new string message an empty string.

`StringMessage(const char* name)`
: Create a new string message with a copy of the given string. The given string can be deleted, since the new message does not reference it.

`StringMessage(const StringMessage& src)`
: Create a new string message containing the same string as the given string message. Again, the string is copied.

Operations

`StringList print()`
: Return the string contained in this message in a StringList object.

4.6 Writing Stars That Manipulate Any Particle Type

Ptolemy allows stars to declare that inputs and outputs are of type ANYTYPE. A star may need to do this, for example, if it simply copies its inputs without regard to type, as in the case of a Fork star, or if it calls a generic function that is overloaded by every data type, such as sink stars which call the print method of the type.

The following is an example of a star that operates on ANYTYPE particles:

```
defstar {
      name {Fork}
      domain {SDF}
      desc { Copy input particles to each output. }
      input {
            name{input}
            type{ANYTYPE}
      }
      outmulti {
            name{output}
            type{= input}
      }
      go {
```

```
                MPHIter nextp(output);
                PortHole* p;
                while ((p = nextp++) != 0)
                      (*p)%0 = input%0;
        }
}
```

Notice how in the definition of the output type, the star simply says that its output type will be the same as the input type. ptlang translates this definition into an `ANYTYPE` output porthole and a statement in the star constructor that reads

```
output.inheritTypeFrom(input);
```

as you can see by examining the `.cc` file generated for `SDFFork`.

During galaxy setup, the Ptolemy kernel assigns actual types to `ANYTYPE` portholes, making use of the types of connected portholes and inheritTypeFrom connections. For example, if a Fork's input is connected to an output porthole of type `INT`, the Fork's input becomes type `INT`, and then so do its output(s) thanks to the inheritTypeFrom connection. At runtime there is no such thing as an `ANYTYPE` porthole; every porthole has been resolved to some specific data type, which can be obtained from the porthole using the `resolvedType()` method. (However, this mechanism does not distinguish among the various subclasses of `Message`, so if you are using `Message` particles you still need to check the actual type of each `Message` received.)

Porthole type assignment is really a fairly complex and subtle algorithm, which is discussed further in the Ptolemy Kernel Manual. The important properties for a star writer to know are these:

- If an input port has a specific declared type, it is guaranteed to receive particles of that type. For reasons mentioned in "Reading inputs and writing outputs" on page 2-17, it is safest to explicitly cast input particles to the desired type, as in

  ```
  go {
        double value = double(in%0);
        ...
  }
  ```

  but this is not strictly necessary in the current system.

- In simulation domains, an output port is NOT guaranteed to transmit particles of its declared type; the actual resolved type of the porthole will be determined by the connected input porthole. Therefore, you should always allow for type conversion of the value computed by the star into the actual type of the output particle. This happens implicitly when you write something like

  ```
  out%0 << t;
  ```

  because this expands into a call of the particle's virtual method for loading a value of the given type. But assuming that you know the exact type of particle in the porthole --- say by writing something like `(FloatParticle&) (out%0)` --- is very unsafe.

- In code generation domains, it is usually critical that the output porthole's actual type be what the star writer expected. Most codegen domains therefore splice type conver-

sion stars into the schematic when input and output ports of different declared types are connected. In this way, both connected stars will see the data type they expect, and the necessary type conversion is handled transparently.

- The component portholes of a multiporthole are type-resolved separately. Thus, if an input multiporthole is declared ANYTYPE, its component portholes might have different types at runtime. (This was not true in Ptolemy versions preceding 0.7.) The component portholes of an output multiporthole can have different resolved types in any case, because they might be connected to inputs of different types.
- It is rarely a good idea to declare a pure ANYTYPE output porthole; rather, its type should be equated to some input porthole using the ptlang `= port` notation or an explicit inheritTypeFrom call. This ensures that the type resolution algorithm can succeed. A "pure ANYTYPE" output will work only if connected to an input of determinable type; if it's connected to an ANYTYPE input, the kernel will be unable to resolve a type for the connection. By providing an `= type` declaration, you allow the kernel to choose an appropriate particle type for an ANYTYPE-to-ANYTYPE connection.

4.7 Unsupported Types

There are a number of data types in Ptolemy that we recommend not be used by external developers because they are either insufficiently mature or likely to change. This section briefly describes those classes.

4.7.1 Sub-matrices

The Ptolemy kernel contains a set of matrices to support efficient computation with sub-matrices. These classes were developed specifically for the experimental multidimensional SDF (MDSDF) domain and will probably be implemented differently in a future release.

There are four sub-matrix classes, one for each concrete matrix class: `ComplexSubMatrix`, `FixSubMatrix`, `FloatSubMatrix`, and `IntSubMatrix`, each of which inherits from the corresponding `PtMatrix` class. A sub-matrix contains a reference to a "parent" matrix of the same type, and modifies its internal data pointers and matrix size parameters to reference a rectangular region of the parent's data. The constructors for the submatrix classes have arguments that specify the region of the parent matrix referenced by the sub-matrix.

As for matrices, the description of sub-matrices uses the convention that `XXX` means `Complex`, `Fix`, `Float`, or `Int`, and `xxx` means `Complex`, `Fix`, `double`, or `int`.

The submatrix constructors are:

`XXXSubMatrix()`
: Create an uninitialized matrix.

`XXXSubMatrix(int numRow, int numCol)`
: Create a regular matrix with dimensions `numRow` by `numCol`; return a new submatrix with this matrix as its parent. Memory is allocated for the data storage but the entries are uninitialized.

```
XXXSubMatrix(XXXSubMatrix& src, int sRow, int sCol, int nRow,
```

`int nCol)`
Create a sub-matrix of the given dimensions and initialize it to reference the region of the parent matrix starting at (`sRow`, `sCol`) and of size (`nRow`, `nCol`). The parent matrix is the same as the parent matrix of `src`. The given dimensions must fit into the parent matrix, or an error will be flagged. Unlike the "sub-matrix" constructors in the regular matrix classes, this constructor does not copy matrix data.

`XXXSubMatrix(const XXXSubMatrix& src)`
Make a duplicate of the `src` sub-matrix. The parent of the new matrix is the same as the parent of `src`.

Submatrices support all operations supported by the regular matrix classes. Because the matrix classes uniformly use only the `entry()` and `operator []` member functions to access the data, the sub-matrix classes need only to override these functions, and all matrix operations become available on sub-matrices.

`xxx& entry(int i)`
Return the i^{th} entry of the sub-matrix when its data storage is considered to be a linear array.

`xxx* operator [] (int row)`
Return a pointer to the start of the row of the sub-matrix's data storage.

Using sub-matrices in stars

Sub-matrices are not currently useful in general-purpose dataflow stars. Rather, they were developed to provide an efficient means of referencing portions of a single larger matrix in the multi-dimensional synchronous dataflow (MDSDF) domain. We give here a summary. For more details, see [Che94] and the MDSDF sources in `$PTOLEMY/src/domains/mdsdf/kernel` and `$PTOLEMY/src/domains/mdsdf/stars`.

Unlike other domains, the MDSDF kernel does not transfer particles through FIFO buffers. Instead, each geodesic keeps a single copy of a "parent" matrix, that represents the "current" two-dimensional datablock. Each time a star fires, it obtains a sub-matrix that references this parent matrix with the `getOutput()` function of the MDSDF input port class. For example, a star might contain:

```
FloatSubMatrix* data = (FloatSubMatrix*)(input.getInput());
```

Note that this is not really getting a matrix, but a sub-matrix that references a region of the current data matrix. The size of the sub-matrix has been set by the star in its initialization code by calling the `setMDSDFParams()` function of the port.

To write data to the output matrix, the star gets a sub-matrix which references a region of the current output matrix and writes to it with a matrix operator. For example,

```
FloatSubMatrix* result = (FloatSubMatrix*)(output.getOutput());
result = -data;
```

Because the sub-matrices are only references to the current matrix on each arc they must be deleted after use:

```
delete &input;
delete &result;
```

Here is a simplified example of a complete MDSDF star:

```
defstar {
      name { Add }
      domain { MDSDF }
      desc {
            Matrix addition of two input matrices A and B to
            produce matrix C. All matrices must have the same
            dimensions.
      }
      version { %W% %G% }
      author { Mike J. Chen }
      location  { MDSDF library }
      input {
            name { Ainput }
            type { FLOAT_MATRIX }
      }
      input {
            name { Binput }
            type { FLOAT_MATRIX }
      }
      output {
            name { output }
            type { FLOAT_MATRIX }
      }
      defstate {
            name { numRows }
            type { int }
            default { 2 }
            desc { The number of rows in the input/output matrices. }
      }
      defstate {
            name { numCols }
            type { int }
            default { 2 }
            desc { The number of columns in the input/output
                        matrices. }
      }
      ccinclude { “SubMatrix.h” }
      setup {
          Ainput.setMDSDFParams(int(numRows), int(numCols));
          Binput.setMDSDFParams(int(numRows), int(numCols));
          output.setMDSDFParams(int(numRows), int(numCols));
      }
      go {
      // get a SubMatrix from the buffer
            FloatSubMatrix& input1
```

```
                        = *(FloatSubMatrix*)(Ainput.getInput());
            FloatSubMatrix& input2
                        = *(FloatSubMatrix*)(Binput.getInput());
            FloatSubMatrix& result
                        = *(FloatSubMatrix*)(output.getOutput());

// compute product, putting result into output

            result = input1 + input2;

            delete &input1;
            delete &input2;
            delete &result;
      }
}
```

The sub-matrix “particles”

The `ptlang` type of submatrices is `FLOAT_MATRIX`, `INT_MATRIX`, and so on. (This is not documented in the *User’s Manual* and is likely to change in a future release.) Each of these ptlang types is implemented by a sub-class of Particle: `IntMatrixParticle`, `Float-MatrixParticle`, `FixMatrixParticle` and `ComplexMatrixParticle`. These particle classes exist only for setting up the portholes and performing type-checking—they are never created or passed around during a simulation. Instead, sub-matrices are created and destroyed by the MDSDF kernel and stars as described above.

4.7.2 Image particles

A set of experimental image data types, designed to make it convenient to manipulate images and video sequences in Ptolemy, were defined by Paul Haskell. They are based on Ptolemy’s built-in `Message` type, described above. A library of stars that uses these image data types can be found in the image library of the DE domain.

This set of classes is being replaced by the `PtMatrix` classes, and the SDF image classes now all use `PtMatrix`. We give here a brief introduction to the image data types used in the DE domain, although new work should consider using `PtMatrix` classes instead. Class definitions can be found in `$PTOLEMY/src/domains/de/kernel`.

The base class of all the image classes is called `BaseImage`. It has some generic methods and members for manipulating images. Most of the methods are redefined in the derived classes. The `fragment` method partitions an image into many smaller images, which together represent the same picture as the original. The `assemble` method combines many small images which make up a single picture into a single image that contains the picture. The `fragment` method works recursively, so an image that has been produced by a previous `fragment` call can be further fragmented. Assembly always produces a full-sized image from fragments, however small.

Use of the `size`, `fullSize`, and `startPos` members varies within each subclass. Typically the `size` variable holds the number of pixels that an object is storing. If an object is not produced by `fragment()`, then (`size == fullSize`). If the object is produced by a `fragment()` call, `size` may be less than or equal to `fullSize`. An objects’s `fullSize` may be bigger or smaller than `width*height`. It would be bigger, for example, in `DCTIm-`

age, where the amount of allocated storage must be rounded up to be a multiple of the block-size. It would be smaller, for example, for an object that contains run-length coded video.

The frameId variable is used during assembly. Fragments with the same frameId's are assembled into the same image. So, it is important that different frames from the same source have different frameIds.

The comparison functions {==, !=, <, >, etc.} compare two objects' frameId's. They can be used to resequence images or to sort image fragments.

The copy constructor and clone methods have an optional integer argument. If a non-zero argument is provided, then all state values of the copied object are copied to the created object, but none of the image data is copied. If no argument or a zero argument is provided, then the image data is copied as well. Classes derived from BaseImage should maintain this policy.

The GrayImage class, derived from BaseImage, is used to represent gray-scale images. The DCTImage class is used to represent images or image fragments that have been encoded using the discrete-cosine transform. The MVImage class is a bit more specialized; it stores a frame's worth of motion vectors.

4.7.3 "First-class" types

All of the types built-in to the Ptolemy kernel are "first-class" in the sense that they are understood by pigi and ptlang. We recommend that users create their own types using the mechanism described in "Defining New Data Types" on page 4-14. This approach has the disadvantage that all user-defined types are seen by pigi and ptlang as being of type "message." If this is not acceptable, then it is possible to create your own first-class types by subclassing Particle and adding the new types to VEM. The following instructions briefly describes this process. We stress, however, that this method is not officially supported and that types created this way will probably have to be reworked in a future release of Ptolemy. You will need to use some other color—say fileColor—as a sample to follow when modifying the various source files.

- Sub-class Particle and Message. Use the classes in $PTOLEMY/src/kernel/FileMessage.h/cc and $PTOLEMY/src/kernel/FileParticle.{h,cc} as examples. You will need to create a static instance of your Particle and static Plasma and PlasmaGate instances to hold your particles, as demonstrated by FileParticle.
- Modify $PTOLEMY/src/pigilib/mkTerm.c. There are three switch statements where you will need to insert a new case.
- In the directory $PTOLEMY/lib/colors/ptolemy, edit bw.pat and colors.pat to add the new color. The color is in RBG format, with 1000 being full-scale.
- Run the Octtools installColors program. It will ask you a series of mysterious and strangely beautiful questions. To start with, use the defaults, except for "Output display type", where you answer GENERIC-COLOR. Run the same program again with the following output display types: GENERIC-BW, Postscript-Color, and Postscript-BW.
- To support monochrome screens (when pigi is started with the -bw option), repeat

the above, but specify `$PTOLEMY/lib/colors/ptolemy/bw.pat` as the pattern file, `$PTOLEMY/lib/bw_patterns` as the directory in which to install, `GENERIC-COLOR` as the display device, and answer `YES` to the question about color output device.

- After rebuilding `pigilib` and restarting, create an icon for a star that has your new type as an input or output. The terminal should be of the new color.

Chapter 5. Using Tcl/Tk

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5.1 Introduction

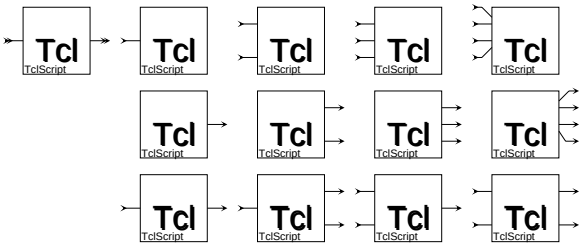
`Tcl` is an interpreted "tool command language" designed by John Ousterhout while at UC Berkeley. `Tk` is an associated X window toolkit. Both have been integrated into Ptolemy. Parts of the graphical user interface and all of the textual interpreter `ptcl` are designed using them. Several of the stars in the standard star library also use Tcl/Tk. This chapter explains how to use the most basic of these stars, `TclScript`, as well how to design such stars from scratch. It is possible to define very sophisticated, totally customized user interfaces using this mechanism.

In this chapter, we assume the reader is familiar with the Tcl language. Documentation is provided along with the Ptolemy distribution in the `$PTOLEMY/tcltk/itcl/man` directory in Unix man page format. HTML format documentation is available from the other.src tar file in `$PTOLEMY/src/tcltk`. Up-to-date documentation and software releases are available by on the SunScript web page at `http://www.sunscript.com`. There is also a newsgroup called `comp.lang.tcl`. This news group accumulates a list of frequently asked questions about Tcl which is available `http://www.teraform.com/%7Elvirden/tcl-faq/`.

The principal use of Tcl/Tk in Ptolemy is to customize the user interface. Stars can be created that interact with the user in specialized ways, by creating customized displays or by soliciting graphical inputs.

5.2 Writing Tcl/Tk scripts for the TclScript star

Several of the domains in Ptolemy have a star called `TclScript`. This star provides the quickest and easiest path to a customized user interface. The icon can take any number of forms, including the following:



All of these icons refer to the same star, but each has been customized for a particular number of input and output ports. You should select the one you need on the basis of the number of

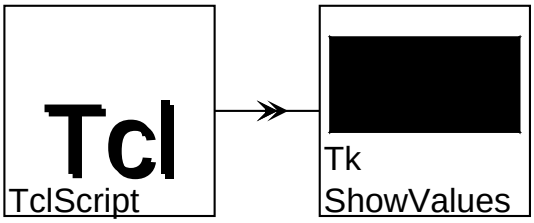
input and output ports required. The left-most icon has an unspecified number of inputs and outputs (as indicated by the double arrows at its input and output ports).

The `TclScript` star has one parameter (settable state):

tcl_file A string giving the full path name of a file containing a Tcl script

The Tcl script file specifies initialization commands, for example to open new windows on the screen, and may optionally define a procedure to be invoked by the star every time it runs. We begin with two examples that illustrate most of the key techniques needed to use this star:

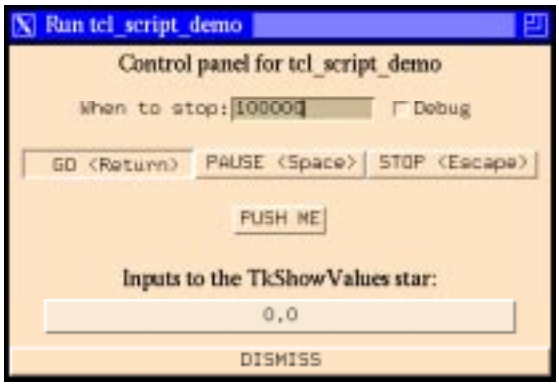
Example 1: Consider the following simple schematic in the SDF domain:



The `TkShowValues` star is in the standard SDF star library. It displays whatever input values are supplied in a subpanel of the control panel for the system. Suppose we specify the following Tcl script for the `TclScript` star:

```
set s $ptkControlPanel.middle.button_$starID
if {! [winfo exists $s]} {
      button $s -text "PUSH ME"
      pack append $ptkControlPanel.middle $s {top}
      bind $s <ButtonPress-1> "setOutputs_$starID 1.0"
      bind $s <ButtonRelease-1> "setOutputs_$starID 0.0"
      setOutputs_$starID 0.0
}
unset s
```

This script creates a pushbutton in the control panel. When the button is depressed, the star outputs the value 1.0. When the button is released, the star outputs value 0.0. The resulting control panel is shown below:



While the system is running, depressing the button labeled “PUSH ME” will cause the value displayed at the bottom to change from 0.0 to 1.0. Releasing the button will change the value back to 0.0. The lines in the Tcl script are explained below:

```
set s $ptkControlPanel.middle.button_$starID
```

This defines a Tcl variable "s" whose value is the name of the window to be used for the button. The first part of the name, `$ptkControlPanel`, is a global variable giving the name of the control panel window itself. This global variable has been set by pigi and can be used by any Tcl script. The second part, `.middle`, specifies that the button should appear in the subwindow named `.middle` of the control panel. The control panel, by default, has empty subwindows named `.high`, `.middle`, and `.low`. The last part, `.button_$starID`, gives a unique name to the button itself. The Tcl variable `starID` has been set by the `TclScript` star to a name that is guaranteed to be unique for each instance of the star. Using a unique name for the button permits multiple instances of the star in a schematic to create separate buttons in the control window without conflict.

```
if {! [winfo exists $s]} {
        ...
}
```

This conditionally checks to see whether or not the button already exists. If, for example, the system is being run a second time, then there is no need to create the button a second time. In fact, an attempt to do so will generate an error message. If the button does not already exist, then it is created by the following lines:

```
button $s -text "PUSH ME"
pack append $ptkControlPanel.middle $s {top}
```

The first of these defines the button, and the second packs it into the control panel (see the Tk documentation). The following Tcl statement binds a particular command to a mouse action, thus defining the response when the button is pushed:

```
bind $s <ButtonPress-1> "setOutputs_$starID 1.0"
```

When button number 1 of the mouse is pressed, the Tcl interpreter invokes a procedure named `setOutputs_$starID` with a single argument, `1.0` (passed as a string). This procedure has been defined by the `TclScript` star. It sets the value(s) of the outputs of the star. In this case, there is only one output, so there is only one argument. The next statement defines the action when the button is released:

```
bind $s <ButtonRelease-1> "setOutputs_$starID 0.0"
```

The next statement initializes the output of the star to value 0.0:

```
setOutputs_$starID 0.0
```

The last command unsets the variable s, since it is no longer needed:

```
unset s
```

As illustrated in the previous example, a number of procedures and global variables will have been defined for use by the Tcl script by the time it is sourced. These enable the script to modify the control panel, define unique window names, and set initial output values for the star. Much of the complexity in the above example is due to the need to use unique names for each star instance that sources this script. In the above example, the Tcl procedure for setting the output values has a name unique to this star. Moreover, the name of the button in the control panel has to be unique to handle the case when more than one `TclScript` star sources the same Tcl script. These unique names are constructed using a unique string defined by the star prior to sourcing the script. That string is made available to the Tcl script in the form of a global Tcl variable `starID`. The procedure used by the Tcl script to set output values is called `setOutputs_$starID`. This procedure takes as many arguments as there are output ports. The argument list should contain a floating-point value for each output of the star.

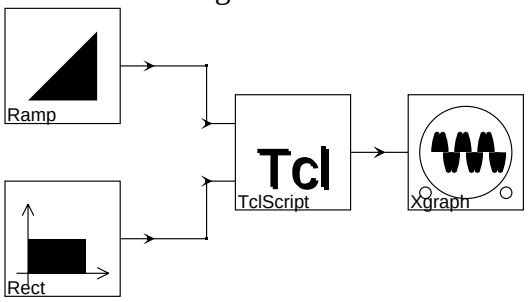
In the above example, Tcl code is executed when the Tcl script is sourced. This occurs during the setup phase of the execution of the star. After the setup phase, no Tcl code will be executed unless the user pushes the “PUSH ME” button. The command

```
bind $s <ButtonPress-1> "setOutputs_$starID 1.0"
```

defines a Tcl command to be executed asynchronously. Notice that the command is enclosed in quotation marks, not braces. Tcl aficionados will recognize that this is necessary to ensure that the `starID` variable is evaluated when the command binding occurs (when the script is sourced), rather than when the command is executed. There is no guarantee that the variable will be set when the command is executed.

In the above example, no Tcl code is executed when the star fires. The following example shows how to define Tcl code to be executed each time the star fires, and also how to read the inputs of the star from Tcl.

Example 2: Consider the following schematic in the SDF domain:



Suppose we specify the following Tcl script for the `TclScript` star:

```
proc goTcl_$starID {starID} {
     set inputVals [grabInputs_$starID]
     set xin [lindex $inputVals 0]
     set yin [lindex $inputVals 1]
     setOutputs_$starID [expr $xin+$yin]
}
```

Unlike the previous example, this script does not define any code that runs when the script is sourced, during the setup phase of execution of the star. Instead, it simply defines a procedure with a name unique to the instance of the star. This procedure reads two input values, adds them, and writes the result to the output. Although this would be a very costly way to accomplish addition in Ptolemy, this example nonetheless illustrates an important point. If a Tcl script sourced by a `TclScript` star defines a procedure called `goTcl_$starID`, then that procedure will be invoked every time the star fires. The single argument passed to the procedure when it is called is the `starID`. In this example, the procedure uses `grabInputs_$starID`, defined by the `TclScript` star, to read the inputs. The current input values are returned by this procedure as a list, so the Tcl command `lindex` is used to index into the list. The final line adds the two inputs and sends the result to the output.

As shown in the previous example, if the Tcl script defines the optional Tcl procedure `goTcl_$starID`, then that procedure will be invoked every time the star fires. It takes one argument (the `starID`) and returns nothing. This procedure, therefore, allows for *synchronous* communication between the Ptolemy simulation and the Tcl code (it is synchronized to the firing of the star). If no `goTcl_$starID` procedure is defined, then communication is *asynchronous* (Tcl commands are invoked at arbitrary times, as specified when the script is read). For asynchronous operation, typically X events are bound to Tcl/Tk commands that read or write data to the star.

The inputs to the star can be of any type. The `print()` method of the particle is used to construct a string passed to Tcl. Although it is not illustrated in the above examples, asynchronous reads of the star inputs are also allowed.

Below is a summary of the Tcl procedures used when executing a `TclScript` star:

`grabInputs_$starID`
: A procedure that returns the current values of the inputs of the star corresponding to the given `starID`. This procedure is defined by the `TclScript` star if and only if the instance of the star has at least one input port.

`setOutputs_$starID`
: A procedure that takes one argument for each output of the `TclScript` star. The value becomes the new output value for the star. This procedure is defined by the `TclScript` star if and only if the instance of the star has at least one output port.

`goTcl_$starID`
: If this procedure is defined in the Tcl script associated with an instance of the `TclScript` star, then it will be invoked every time the star fires.

`wrapupTcl_$starID`
: If this procedure is defined in the Tcl script associated with an instance of the `TclScript` star, then it will be invoked every

time the `wrapup` method of the star is invoked. In other words, it will be invoked when a simulation stops.

`destructorTcl_$starID`
: If this procedure is defined in the Tcl script associated with an instance of the `TclScript` star, then it will be invoked when the destructor for the star is invoked. This can be used to destroy windows or to unset variables that will no longer be needed.

In addition to the `starID` global variable, the `TclScript` star makes other information available to the Tcl script. The mechanism used is to define an array with a name equal to the value of the `starID` variable. Tcl arrays are indexed by strings. Thus, not only is `starID` a global variable, but so is `$starID`. The value of the former is a unique string, while the value of the latter is an array. One of the entries in this array gives the number of inputs that are connected to the star. The value of the expression `[set ${starID}(numInputs)]` is an integer giving the number of inputs. The Tcl command "`set`", when given only one argument, returns the value of the variable whose name is given by that argument. The array entries are summarized below:

`$starID`
: This evaluates to a string that is different for every instance of the `TclScript` star. The `starID` global variable is set by the `TclScript` star.

`[set ${starID}(numInputs)]`
: This evaluates to the number of inputs that are connected to the star.

`[set ${starID}(numOutputs)]`
: This evaluates to the number of outputs that are connected to the star.

`[set ${starID}(tcl_file)]`
: This evaluates to the name of the file containing the Tcl script associated with the star.

`[set ${starID}(fullName)]`
: This evaluates to the full name of the star (which is of the form universe.galaxy.galaxy.star).

5.3 Tcl utilities that are available to the programmer

A number of Tcl global variables and procedures that will be useful to the Tcl programmer have been incorporated into Ptolemy. Any of these can be used in any Tcl script associated with an instance of the `TclScript` star. For example, in example 1 on page 5-2, the global variable `ptkControlPanel` specifies the control panel that is used to run the system. Below is a list of the useful global variables that have been set by the graphical interface (`pigi`) when the Tcl script is sourced or when the `goTcl_$starID` procedure is invoked:

`$ptkControlPanel` A string giving the name of the control panel window associated with a given run. This variable is set by pigi.

`$ptkControlPanel.high`
: The uppermost panel in the control panel that is intended for user-defined entries.

`$ptkControlPanel.middle`
: The middle panel in the control panel that is intended for user-defined entries.

`$ptkControlPanel.low`
: The lowest panel in the control panel that is intended for user-defined entries.

In addition to these global variables, a number of procedures have been supplied. Using these procedures can ensure a consistent look-and-feel across a variety of Ptolemy applications. The complete set of procedures can be found in `$PTOLEMY/lib/tcl`. We list a few of the more useful ones here. Note also that the entire set of commands defined in the Tcl-based textual interpreter for Ptolemy, `ptcl`, are also available. So for example, the command `curuniverse` will return the name of the current universe. See the `ptcl` chapter in the *User's Manual*.

`ptkExpandEnvVar`
: Procedure to expand a string that begins with an environment variable reference. For example,
```
ptkExpandEnvVar $PTOLEMY/src
```
will return something like
```
/usr/users/ptolemy/src
```
Arguments:

path	the string to expand

`ptkImportantMessage`
: Procedure to pop up a message window and grab the focus. The process is suspended until the message is dismissed.
Arguments:

win	window name to use for the message
text	text to display in the pop-up window

`ptkMakeButton`
: Procedure to make a pushbutton in a window. A callback procedure must be defined by the programmer. It will be called whenever the user pushes the button, and takes no arguments.
Arguments:

win	name of window to contain the button
name	name to use for the button itself
desc	description to be put into the display
callback	name of callback procedure to register changes

`ptkMakeEntry`
: Procedure to make a text entry box in a window. A callback procedure must be defined by the programmer. It will be called whenever the user changes the value in the entry box and types

<Return>. Its single argument will be the new value of the entry.

Arguments:

win	name of window to contain the entry box
name	name to use for the entry box itself
desc	description to be put into the display
default	the initial value of the entry
callback	name of callback procedure to register changes

`ptkMakeMeter` Procedure to make a bar-type meter in a window.

Arguments:

win	name of window to contain the entry box
name	name to use for the entry box itself
desc	description to be put into the display
low	the value of the low end of the scale
high	the value of the high end of the scale

`ptkSetMeter` Procedure to set the value of a bar-type meter created with `ptkMakeMeter`.

Arguments:

win	name of window to contain the entry box
name	name to use for the entry box itself
value	the new value to display in the meter

`ptkMakeScale` Procedure to make a sliding scale. All scales in the control panel range from 0 to 100. A callback procedure must be defined by the programmer. It will be called whenever the user moves the control on the scale. Its single argument will be the new position of the control, between 0 and 100.

Arguments:

win	name of window to contain the scale
name	name to use for the scale itself
desc	description to be put into the display
position	initial integer position between 0 and 100
callback	name of callback procedure to register changes

Note:

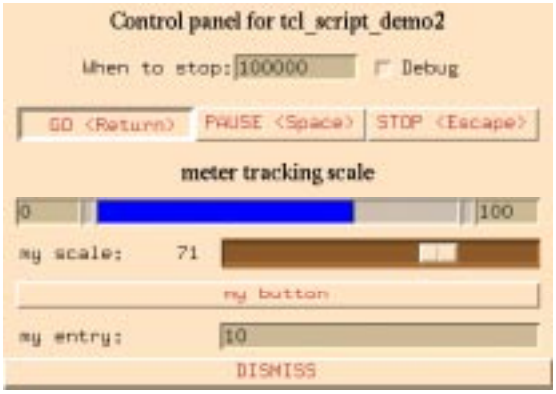
A widget is created with name `$win.$name.value` that should be used by the programmer to display the current value of the slider. Thus, the callback procedure should contain a command like:

`$win.$name.value configure -text $new_value`
to display the new value after the slider has been moved. This is not performed automatically because the fixed range from 0 to 100 may be correct from the user's perspective. So, for example, if you divide the scale value by 100 before displaying it, then to the user, it will appear as if the scale ranges from 0.0 to 1.0. It is also possible to control the position of the slider from Tcl (overriding the user actions) using a command like
`$win.$name.scale set $position`
where `position` is an integer-valued variable in the range of 0 to 100.

Example 3: The following Tcl script can be used with the `TclScript` star in the system configuration given in example 1 on page 5-2:

```
ptkMakeMeter $ptkControlPanel.high meter_$starID \
      "meter tracking scale" 0 100
proc scale_update_$starID {new_value} \
      "ptkSetMeter $ptkControlPanel.high \
            meter_$starID \$new_value
       $ptkControlPanel.high.scale_$starID.value \
            configure -text \$new_value"
ptkMakeScale $ptkControlPanel.high scale_$starID \
      "my scale" 50 scale_update_$starID
ptkMakeButton $ptkControlPanel.middle button_$starID \
      "my button" button_update
proc button_update {} {ptkImportantMessage .msg "Hello"}
ptkMakeEntry $ptkControlPanel.low entry_$starID \
      "my entry" 10 entry_update_$starID
proc entry_update_$starID {new_value} \
      "setOutputs_$starID \$new_value"
```

It will create the rather ugly control panel shown below:



The commands are explained individually below.

```
ptkMakeMeter $ptkControlPanel.high meter_$starID \
```

```
        "meter tracking scale" 0 100
```

This creates a meter display with the label “meter tracking scale” in the upper part of the control panel with range from 0 to 100.

```
proc scale_update_$starID {new_value} \
     "ptkSetMeter $ptkControlPanel.high \
          meter_$starID \$new_value
      $ptkControlPanel.high.scale_$starID.value \
          configure -text \$new_value"
```

This defines the callback function to be used for the slider (scale) shown below the meter. The callback function sets the meter and updates the numeric display to the left of the slider. Notice that the body of the procedure is enclosed in quotation marks rather than the usual braces. This ensures that the variables `ptkControlPanel` and `starID` will be evaluated at the time the procedure is defined, rather than at the time it is invoked. To make sure that `new_value` is not evaluated until the procedure is invoked, we use a preceding backslash, as in `\$new_value`. We could have alternatively passed the `ptkControlPanel` and `starID` values as arguments.

```
ptkMakeScale $ptkControlPanel.high scale_$starID \
     my_scale 50 scale_update_$starID
```

This makes the slider itself, and sets its initial value to 50, half of full scale.

```
ptkMakeButton $ptkControlPanel.middle button_$starID \
     "my button" button_update
```

This makes a button labeled “my button”.

```
proc button_update {} {ptkImportantMessage .msg "Hello"}
```

This defines the callback function connected with the button. This callback function opens a new window with the message “Hello”, and grabs the focus. The user must dismiss the new window before continuing.

```
ptkMakeEntry $ptkControlPanel.low entry_$starID \
     "my entry" 10 entry_update_$starID
```

This makes the entry box with initial value “10”.

```
proc entry_update_$starID {new_value} \
     "setOutputs_$starID \$new_value"
```

This defines the callback function associated with the entry box. Again notice that the procedure body is enclosed quotation marks.

5.4 Creating new stars derived from the TclScript star

A large number of useful stars can be derived from the `TclScript` star. The `TkShowValues` star used in example 1 on page 5-2 is such a star. That star takes inputs of any type and displays their value in a window that is optionally located in the control panel. It has three parameters (settable states):

label A string-valued parameter giving a label to identify the display.

put_in_control_panel A Boolean-valued parameter that specifies whether the display should be put in the control panel or in its own window.

wait_between_outputs A Boolean-valued parameter that specifies whether the execution of the system should pause each time a new value is displayed. If it does, then a mouse click in the display restarts the system.

Conspicuously absent is the *tcl_file* parameter of the `TclScript` star from which this is derived. The file is hard-wired into the definition of the star by the following C++ statement included in the setup method:

```
tcl_file =
"$PTOLEMY/src/domains/sdf/tcltk/stars/tkShowValues.tcl";
```

The parameter is then hidden from the user of the star by the following statement included in the constructor:

```
tcl_file.clearAttributes(A_SETTABLE);
```

Thus, the user sees only the parameters that are defined in the derived star. This is a key part of customizing the star.

A second issue is that of communicating the new parameter values to the Tcl script. For example, the Tcl script will need to know the value of the *label* parameter in order to create the label for the display. The `TclScript` star automatically makes all the parameters of any derived star available as array entries in the global array whose name is given by the global variable `starID.` To read the value of the *label* parameter in the Tcl script, use the expression `[set ${starID}(label)]`. The confusing syntax is required to ensure that Tcl uses the *value* of `starID` as the *name* of the array. The string “label” is just the index into the array. The `set` command in Tcl, when given only one argument, returns the value of the variable whose name is given by the argument.

Some programmers may prefer an alternative way to refer to parameters that is slightly more readable. The Tcl statement

```
upvar #0 $starID params
```

allows subsequent statement to refer to parameters simply as `$param(param_name)`. The `upvar` command with argument `#0` declares the local variable `params` equivalent to the global variable whose name is given by the value of `starID.`

Many more examples can be found in `$PTOLEMY/src/domains/sdf/tcltk/stars`.

5.5 Selecting colors

Since X window installations do not necessarily use consistent color names, a particular color database has been installed in Ptolemy. The available colors can be found in the file `$PTOLEMY/lib/tcl/ptkColor.tcl`. To access this color database, use the Tcl function

```
ptkColor name
```

which returns a color defined in terms of RGB components. This color can be used anyplace that Tk expects a color. If the given name is not in the color database, the color returned is black.

5.6 Writing Tcl stars for the DE domain

In the discrete-event (DE) domain, stars are fired in chronological order according to the time stamps of the new data that has arrived at their input ports. The Tcl interface class `TclStarIfc`, which was originally written with the SDF domain in mind, works well for some types of DE stars. Specifically, any star with an input in the DE domain can use this class effectively. Consequently, a basic Tcl/Tk star, `TclScript`, has been written for the DE domain.

The `TclScript` star can have any number of input or output portholes. As of this writing, it will not work if it is instantiated with no inputs. The problem is that with no inputs, there will be no events to trigger a firing of the star. This will be corrected in the future.

Chapter 6. Using the Cluster Class for Scheduling

Authors: *José Luis Pino*

6.1 Introduction

The Ptolemy kernel has three main facilities to aid in the implementation of scheduling algorithms: generic clustering mechanisms, graph iterators, and classical graph algorithms. In this chapter, we will cover the use of these facilities and some of the important methods currently available in Ptolemy to implement new scheduling algorithms.

6.2 Basic Classes

User-specifications done in Ptolemy are represented internally as a collection of annotated directed graphs that may contain cycles. Nodes in these directed graphs may themselves contain other directed graphs. An *atomic* node is either a `Star`, which defines code to implement the node operation, or a `WormHole`, which has an internal graph that is hidden from the outside. A `WormHole` is used when there is a change in the semantics between the internal and external graphs, such as a change in the `Domain` or `Scheduler`. For purposes of the outside graph, a `WormHole` is equivalent to a `Star`. A *non-atomic* node, or `Galaxy`, is a node which contains an internal graph which is visible from the outside. This internal graph is stored in a `Galaxy`'s `BlockList`. Finally, a `Scheduler` is a class that determines the firing order of *atomic* nodes in a graph.

`WormHoles`, `Galaxies` and `Stars` are all derived from the class `Block`. A `Block` contains `PortLists`, which store a list of `PortHoles` that provide locations to connect input or output arcs to the `Block`. `Blocks` also contain `StateLists`, which may either be user-specified parameters or run-time states that are used when a graph is executed.

A user specification is compiled into an internal representation known as an *interpreted universe* (`InterpUniverse`). Currently, the user specifications are in the form of ptcl or oct facets. In the future there will probably be also a Tycho specification format. An `InterpUniverse` captures the user hierarchy in the form of a directed graph of `WormHoles`, `Galaxies` and `Stars`. The `InterpUniverse` is derived from `Galaxy` and contains the top-level user-specification in its `BlockList`. Every other level of the user specified hierarchy is represented by either a `Wormhole` or `Galaxy` embedded inside of its *parent* `Galaxy`.

All `Blocks` have a `parent Block` pointer. The parent of a `Block` is the `Galaxy` or `WormHole` in which the `Block` is embedded. The `InterpUniverse`, which is the top-level `Galaxy` user specification, has its `parent` pointer set to `NULL`.

6.3 Galaxies and their relationship to Adjacency Lists

To define graph algorithms, adjacency-lists and adjacency-matrices are commonly used to represent a directed graph [Cor90]. An adjacency-matrix is a square matrix where

there is one column, *i*, and one row, *j*, for each node, *i*, the graph. An element *(i, j)* in this matrix is either 1 if there is an arc from *i* to *j*, or 0 if no arc exists. The second representation is an adjacency-list in which each node has a list containing the nodes to which it is connected. Thus an adjacency-list is better suited for sparse graphs, whereas adjacency-matrices are well suited for dense graphs.

`Blocks` with their `PortLists` can be viewed as equivalent to the adjacency-list data structure. A `PortHole`, in most domains, is either an input or an output. It contains a `farSidePort` pointer to the `PortHole` it is connected to (`NULL` if it is not connected). To traverse the adjacency-list, a scheduler writer must make use of two iterators in Ptolemy (See "Iterators" on page 3-10): `GalStarIter` and `SuccessorIter`. By using a `GalStarIter` a scheduler writer can iterate over the nodes in the user-specified graph. Then on each of these nodes we can find the adjacent nodes using the `SuccessorIter`. Although it is not necessary for adjacency-list equivalence, the `PredecessorIter` is provided to iterate over the nodes that are predecessors to a given node.

There is slight overhead in accessing the graph using both `GalStarIter` and `SuccessorIter` over a straight forward implementation of an adjacency-list class. This overhead has a constant cost which is not dependent on the size of the graph. Thus we feel that the robustness achieved by not having two parallel representations of the same graph far outweigh this small overhead.

6.4 Clustering

Clustering is often used in implementing scheduling heuristics. We have provided a generic `Cluster` class in the Ptolemy kernel which scheduler writers can use directly or, if need be, derive specialized clustering classes. The older schedulers such as the BDF scheduler and the SDF loop schedulers have not been upgraded to use the new `Cluster` classes. Thus, the BDF and SDF schedulers should not be used as examples of how to do clustering in Ptolemy, but rather the hierarchical SDF parallel scheduler (`$PTOLEMY/src/domains/cg/hierScheduler`) can be used as a model. The `HierScheduler` in the current version of Ptolemy is a prototype of the hierarchical parallel scheduler detailed in [Pin95]. In addition, we have a specialized loop scheduler [Mur94] which also uses the new cluster facilities.

The class `Cluster` is derived from the `DynamicGalaxy` and as such manages its own memory. The `Cluster` classes use `ClusterPorts` which are derived from `GalPort`. The main difference between the `ClusterPorts` and `GalPorts` is that `ClusterPorts` maintain a `farSidePort` pointer. We need this change in `ClusterPort` in order to easily iterate over the `Clusters` at any level of the clustering hierarchy. A `ClusterPort::farSidePort` pointer will only be `NULL` if the `ClusterPort` is aliased to a `Star PortHole` connected at higher level of the clustering hierarchy.

6.4.1 Initialization — Flattening the User Specified Graph

Clustering is done directly on the internal representation of the user-specified graph. Before we can begin to cluster the internal representation, the irrelevant user hierarchy must be flattened. The flattening is accomplished by creating a temporary `Cluster` instance and then invoking the `Cluster::initializeForClustering` method on the `Galaxy` whose internals we want to cluster. This top-level `Galaxy` will remain intact, but all internal `Galax-`

ies which pass the Cluster::flattenGalaxy test will be flattened and deleted. Thus any Scheduler and Target pointers to the top-level Galaxy will not need to be updated because they do not change. The necessary information from the user-specified hierarchy is preserved automatically with the aid of the Scope class detailed in section 6.5.

After the internals of the top-level Galaxy have been flattened, Clusters are constructed around each individual atomic Block. In that way, the scheduler writer can treat all the Blocks at each level (except the innermost level) as a Cluster. This property is maintained through any sequence of merge/absorb calls. An example initializeForClustering invocation is shown in figure 6-1, frames 1 and 2.

A facility for restoring the internal Ptolemy representation back to the original user-specified hierarchy is detailed in section 6.6.

6.4.2 Absorb and Merge

The basic clustering mechanisms are implemented with the virtual methods: Cluster::merge and Cluster::absorb. Both of these methods can take up to two arguments. The first argument is the Cluster to absorb/merge and the second argument(optional) specifies whether or not to remove the absorbed or merged Cluster from the original parent Galaxy.

The Cluster::merge method takes the contents of the Cluster being merged and moves them into the Cluster pointed to by the this pointer. A merge operation is communicative. A series of merge steps is shown in figure 6-1 frames 3 and 4.

The Cluster::absorb method takes the Cluster being absorbed and moves it into the Cluster pointed to by the this pointer. Unlike merge, absorb is not communicative as shown in figure 6-1 frames 5 and 5'.

The absorbed or merged Cluster is removed from the original parent Galaxy by default when Cluster::merge or Cluster::absorb is called. We provide three ways to update the graph after a clustering operation with differing levels of efficiency. These methods are detailed in the table 6-1. We first list some variable definitions:

- Let N be defined as the number of Clusters in the parent Galaxy
- Let E_t be defined as the number of PortHoles in *this* Cluster
- Let E_c be defined as the number of PortHoles in the Cluster to absorb or merge

Deletion/Update Method	Complexity to update at each clustering step
Using merge/absorb in their default mode of operation. This is the most inefficient way to do clustering.	$O(N + E_t \times E_c)$

TABLE 6-1: Complexity cost of absorb/merge step.

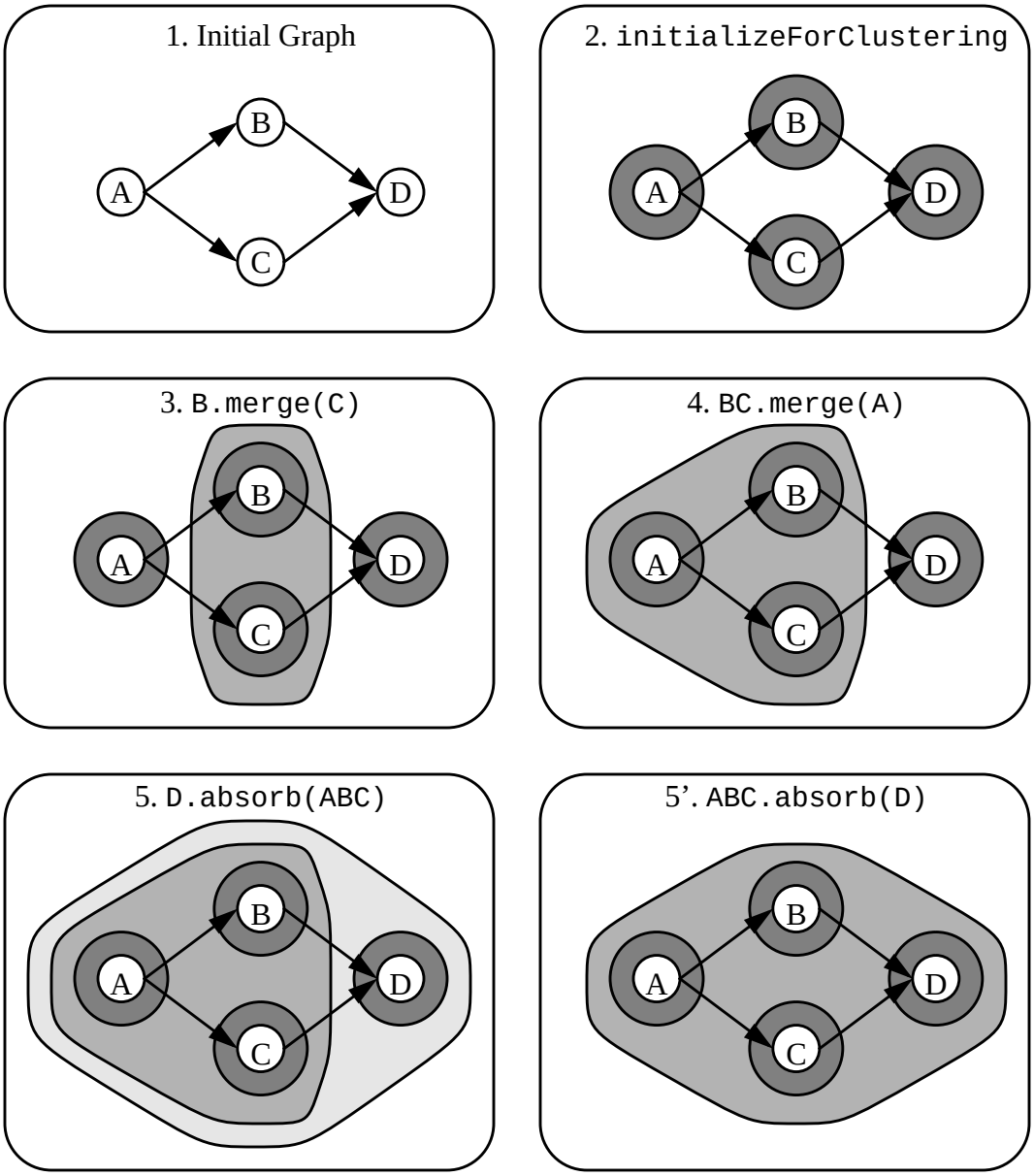


FIGURE 6-1: A five step clustering example. By convention, a `Cluster` in this figure will be named by the listing of its innermost atomic `Blocks`. In frame 1, the user-specified graph is shown. `Cluster::initializeForClustering` is called and the resultant graph is shown in frame 2 — this step adds a `Cluster` around all atomic `Blocks`. Frames 3-5 show a series of merge/absorb operations. The ordering is important only with absorb operation — as shown by frames 5 and 5'.

Deletion/Update Method	Complexity to update at each clustering step
`GalTopBlockIter::remove` We can use this method if the `Cluster` to absorb/merge was found using a `GalTopBlockIter` (or derived iterator class) on the parent `Galaxy`. The scheduler writer needs to do two things: • remove the absorbed/merged cluster using from the parent `Galaxy` using the iterator's `remove` method. • delete the removed `Cluster` using the `C++` operator `delete`. This is the most efficient way of updating the graph after a clustering operation — but it is not always possible because we may be traversing the graph in some other way such as using a `SuccessorIter`.	$O(E_t \times E_c)$
`cleanupAfterCluster` (defined in `Cluster.{h,cc}`) If we cannot use the previous method, we can leave the `Cluster` in the parent `Galaxy` list (it will be marked invalid automatically). The `Cluster` iterator classes automatically skip these invalid `Clusters`. Periodically (but not at each clustering step), the `cleanupAfterCluster` function should be invoked to remove and delete the invalid `Clusters`. This function will cost $O(N + E_t \times E_c)$ to execute, but since it is not done at each clustering step — the result on the overall complexity will be additive versus being multiplicative. For an example of how this is done, refer to: `$PTOLEMY/src/domains/cg/hierScheduler/HierScheduler.cc`.	$O(E_t \times E_c)$

TABLE 6-1: Complexity cost of absorb/merge step.

6.4.3 Cluster Iterator Classes

The `Cluster` iterator classes assume that all `Blocks` in the `Galaxy` being iterated on are `Clusters`. This property is `TRUE` assuming that the `Galaxy` (or one of its parent Galaxies) has been properly initialized (section 6.4.1) and merge/absorb have been the only functions that have modified the topology of the graph since the initialization. These iterators ignore pointers to invalid `Clusters` which have been left in the `Galaxy` using `merge`/`absorb` with the `removeFlag` set to `FALSE` (last two cases in table 6-1). The cluster iterators are listed in table 6-2.

Iterator	Description
`ClusterIter`	Iterate over all valid `Clusters` in the given `Galaxy`.
`SuccessorClusterIter`	Iterate over all successor (adjacent) `Clusters` for a given `Cluster`.

TABLE 6-2: `Cluster` Iterators

Iterator	Description
`PredecessorClusterIter`	Iterate over all predecessor `Clusters` for a given `Cluster`.

TABLE 6-2: `Cluster` Iterators

6.5 Block state and name scoping hierarchy

Recall, that when we initialize a `Galaxy` for clustering, we flatten the original user-specified hierarchy. Before this action, we extract the important information in the hierarchy using the `Scope` class. In this section we detail this class. The details in this section, however, are not necessary to understand clustering in Ptolemy.

`Blocks` inherit states from their parent. The `Scope` class makes it possible for a `Target` or `Scheduler` to change the `Block` hierarchy by saving the inherited states in the user-specified hierarchy. The scoping hierarchy was first released in Ptolemy 0.6, and is only created when the static method `Scope::createScope(Galaxy&)` is invoked. Currently, the only code that uses the scoping hierarchy is the `Cluster` class.

The `Scope` class manages its memory. Once a `Scope` is created, it will not be deleted until all `Blocks` within the given `Scope` are deleted. The `Scope` class is privately derived from `Galaxy`. To turn on scoping a programmer simply calls the static method:

```
static Scope* Scope::createScope(Galaxy&)
```

This method constructs a parallel tree corresponding to each `Galaxy` and copies the `StateList` and `name()` for each level.

6.6 Resetting an InterpUniverse back to actionList

Ptolemy 0.6 and later includes the ability to reset an `InterpUniverse` back to the original user-specification. Resetting is occasionally necessary to undo certain operations done on a universe by a `Scheduler` or `Target`. An example is in parallel scheduling, where the original stars in the `InterpUniverse` are moved to the `subGalaxies` for the child `Targets` (see `$PTOLEMY/src/domains/cg/parScheduler/ParProcessors.cc`). To signal that a the `InterpUniverse` needs to be rebuilt upon the next run, the scheduler writer should invoke `Target::requestReset()`.

6.7 References

[Cor90] Cormen, Leiserson and Rivest, *Introduction to Algorithms*, New York: MIT Press, 1990.

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Chapter 7. SDF Domain

Authors: *Joseph T. Buck*
Soonhoi Ha
Edward A. Lee

7.1 Introduction

Synchronous dataflow (SDF) is a statically scheduled dataflow domain in Ptolemy. "Statically scheduled" means that the firing order of the stars is determined once, during the start-up phase. The firing order will be periodic. The SDF domain in Ptolemy is one of the most mature, with a large library of stars and demo programs. It is a simulation domain, but the model of computation is the same as that used in most of the code generation domains. A number of different schedulers, including parallelizing schedulers, have been developed for this model of computation.

We assume in this very short chapter that the reader is familiar with the SDF model of computation. Refer to the *User's Manual*. Moreover, we assume the reader is familiar with chapter 2, "Writing Stars for Simulation". Since most of the examples given in that chapter are from the SDF domain, there is only a little more information to add here.

7.2 Setting SDF porthole parameters

All stars in the SDF domain must follow the basic SDF principle: the number of particles consumed or produced on any porthole does not change while the simulation runs. These numbers are given for each porthole as part of the star definition. Most stars consume just one particle on each input and produce just one particle on each output. In these cases, no special action is required, since the porthole SDF parameters will be set to unity by default. However, if the numbers differ from unity, the star definition must reflect this. For example, the `FFTCx` star has a *size* parameter that specifies how many input samples to read. The value of that parameter specifies the number of samples required at the input in order for the star to fire. The following line in the `setup` method of the star is used to make this information available to the scheduler:

```
input.setSDFParams (int(size), int(size)-1);
```

The name of the input porthole is *input*. The first argument to `setSDFParams` specifies how many samples are consumed by the star when it fires; it is the same as the number of samples required in order to enable the star. The second argument to `setSDFParams` specifies how many past samples (before the most recent one) will be accessed by the star when it fires.

If the number of particles produced or consumed is a constant independent of any states, then it may be declared right along with the declaration of the input, in the `.pl` file. For example,

```
input {
      name { signalIn }
      type { complex }
```

```
            numTokens { 2 }
            desc { Complex input that consumes 2 input particles. }
        }
```

This declares an input that consumes two successive complex particles.

Chapter 8. DDF Domain

Authors: *Soonhoi Ha*

8.1 Programming Stars in the DDF Domain

A DDF star, as distinct from an SDF star, has at least one porthole, either an input or an output, that receives or sends a variable number of particles. Such portholes are called *dynamic*. Consequently, for a DDF star, how many particles to read or write is determined at run time, in the `go` method. Consider an example, the `LastOfN` star:

```
defstar {
      name {LastOfN}
      domain {DDF}
      desc {
Outputs the last token of N input tokens,
where N is the value of the control input.
      }
      input {
            name {input}
            type {anytype}
            num {0}
      }
      input {
            name {control}
            type {int}
      }
      output {
            name {output}
            type {anytype}
      }
      private {
            int readyToGo;
      }
      constructor {
            input.inheritTypeFrom(output);
      }
      setup {
            waitFor(control);
            readyToGo = FALSE;
      }
      go {
            if (!readyToGo) {
                  control.receiveData();
                  waitFor(input, int (control%0));
                  readyToGo = TRUE;
            } else {
                  int num = int (control%0);
                  for (int i = num; i > 0; i--) input.receiveData();
```

```
                        output%0 = input%0;
                        output.sendData();
                        waitFor(control);
                        readyToGo = FALSE;
                  }
            }
      }
```

The `LastOfN` star discards the first *N-1* particles from the `input` porthole and routes the last one to the `output` porthole . The value *N* is read from the `control` input. Since the control data varies, the number of particles to read from the `input` porthole is variable, as expected for a DDF star. We can specify that the `input` porthole is *dynamic* by setting the `num` field of the `input` declaration to be 0 using the preprocessor format:

```
                  num {0}
```

The firing rule of the star is controlled by the `waitFor` method of the `DDFStar` class (actually, it is defined in the base class, `DynDFStar`). The `waitFor` method takes a porthole as an argument, and an optional integer as a second argument. It indicates that the star should fire when amount of data specified by the integer (default is 1) is available on the specified port. In the above example, the `setup` method specifies that the star should first wait for a `control` input. When a `control` input arrives, the `go` method reads the control value, and uses `waitFor` to specify that the star should fire next when the specified number of inputs have arrived at `input`. The private member `readyToGo` is used to keep track of which input we are waiting for. The line

```
            for (int i = num; i > 0; i--) input.receiveData();
```

causes the appropriate number of inputs (given by `num`) to be consumed.

The next example is a DDF star with a dynamic output porthole: a `DownCounter` star.

```
      defstar {
            name {DownCounter}
            domain {DDF}
            desc { Count down from the input value to zero. }
            input {
                  name {input}
                  type {int}
            }
            output {
                  name {output}
                  type {int}
                  num {0}
            }
            go {
                  input.receiveData();
                  for (int i = int (input%0) - 1 ; i >= 0; i--) {
                        output%0 << i ;
                        output.sendData();
                  }
            }
```

```
}
```

The DownCounter star has a dynamic output porthole that will generate the down-counter sequence of integer data starting from the value read through the input porthole. The code in the go method is self-explanatory.

It is possible, if a bit strange, for a star to alternate between SDF-like behavior and DDF-like behavior. To assert that its next firing should be under SDF rules, the star calls. The following example shows a star that uses the same input for control and data. An integer input specifies the number of particles that will be consumed on the next firing. After these particles have been consumed, the star reverts to SDF behavior to collect the next control input. In the following, readyToGo and num are private integers.

```
setup {
      clearWaitPort();
      readyToGo = FALSE;
}
go {
      int i;
      if (!readyToGo) {
            // get input token from Geodesic
            input.receiveData();
            num = int(input%0);
            waitFor(input, num);
            readyToGo = TRUE;
      } else {
            for (i = 0; i < num; i++) {
                  input.receiveData();
                  output%0 << int(input%0);
                  output.sendData();
            }
            readyToGo = FALSE;
            clearWaitPort();
      }
}
```

Because of the clearWaitPort() in the setup method, the star begins as an SDF star. It consumes one data, stores its value in num, and issues a waitFor command. This changes its behavior to DDF and specifies the number of input tokens that are required. On the next firing, it will read num input tokens and copy them to the output, and then it will revert to SDF behavior.

Chapter 9. BDF Domain

Authors: *Joseph T. Buck*

9.1 Writing BDF Stars

BDF stars are written in almost exactly the same way as SDF stars are written. When the `go` method of the star is executed, it is guaranteed that all required input data are present, and after execution, any particles generated by the star are correctly sent off to their destinations. The only additional thing the star writer must know is how to specify that a porthole is conditional on other portholes. This is accomplished with a method of the class `BDFPortHole` called `setBDFParams`.

The `setBDFParams` method takes four arguments. The first argument is the number of particles transferred by the port when the port is enabled. Note that unconditional ports are always enabled. The second argument is either a pointer or a reference to another `BDFPortHole`, which is called the associated port (the function has two overloaded forms, which is why the argument may be specified either as a pointer or as a reference). The third argument is a code specifying the relation between the porthole this method is called on and the associated port:

`BDF_NONE` This code indicates no relation at all.

`BDF_TRUE` This code indicates that data are transferred by the port only when the conditional port has a `TRUE` particle.

`BDF_FALSE` This code indicates that data are transferred by the port only when the conditional port has a `FALSE` particle.

`BDF_SAME` This code indicates that the stream transferred by the associated port is the same as the stream transferred by this port. This relationship is specified for the BDF `Fork` actor and aids the operation of the clustering algorithm.

`BDF_COMPLEMENT`
This code indicates that the stream transferred by the associated port is the logical complement of the stream transferred by this port. This relationship is specified for the BDF `Not` actor and aids the operation of the clustering algorithm.

The fourth argument for `setBDFParams` is the maximum delay, that is, the largest value that the star may specify as an argument to the `%` operator on that porthole. The default value is zero. This argument serves the same purpose as the second argument to `setSDFParams`.

The `setSDFParams` function may be used on BDF portholes; it does not alter the associated port or the relation type, but does alter the other two parameters of `setBDFParams`. By default, BDF portholes transfer one token, unconditionally.

Calls to `setBDFParams` may be placed in the `setup` method of a star, or alternatively in the constructor if the call does not depend on any parameters of the star. Consider as an example a `Switch` star. This star's functionality is as follows: on each execution, it reads a particle from its control input port. If the value is `TRUE`, it reads a particle from its `trueInput` port; otherwise it reads a particle from its `falseInput` port. In any case, the particle is copied to the output port. Using the `ptlang` preprocessor, the setup method could be written

```
setup {
      trueInput.setBDFParams(1, control, BDF_TRUE, 0);
      falseInput.setBDFParams(1, control, BDF_FALSE, 0);
}
```

and the go method could be written

```
go {
      if (int(control%0))
            output%0 = trueInput%0;
      else
            output%0 = falseInput%0;
}
```

Chapter 10. PN domain

Authors: *Thomas M. Parks*

Other Contributors: *Brian Evans*

10.1 Introduction

The Process Network (PN) domain is an implementation of the theory presented in Thomas M. Parks' thesis [Par95]. The PN domain includes the Synchronous Dataflow (SDF), Boolean Dataflow (BDF), and Dynamic Dataflow (DDF) domains as subdomains. This hierarchical relationship among the domains is shown in the *User's Manual* in Figure 1-2. The model of computation for each domain is a strict subset of the model for the domain that contains it.

The nodes of a program graph, which correspond to processes or dataflow actors, are implemented in Ptolemy by objects derived from the class `Star`. The firing function of a dataflow actor is implemented by the `run` method of `Star`. The edges of the program graph, which correspond to communication channels, are implemented by the class `Geodesic`. A `Geodesic` is a first-in first-out (FIFO) queue that is accessed by the `put` and `get` methods. The connections between stars and geodesics are implemented by the class `PortHole`. Each `PortHole` has an internal buffer. The methods `sendData` and `receiveData` transfer data between this buffer and a `Geodesic` using the `put` and `get` methods.

Several existing domains in Ptolemy, such as SDF and BDF, implement dataflow process networks by scheduling the firings of dataflow actors. The firing of a dataflow actor is implemented as a function call to the `run` method of a `Star` object. A scheduler executes the system as a sequence of function calls. Thus, the repeated actor firings that make up a dataflow process are interleaved with the actor firings of other dataflow processes. Before invoking the `run` method of a `Star`, the scheduler must ensure that enough data is available to satisfy the actor's firing rules. This makes it necessary for a `Star` object to inform the scheduler of the number of tokens it requires from its inputs. With this information, a scheduler can guarantee that an actor will not attempt to read from an empty channel.

By contrast, the PN domain creates a separate thread of execution for each node in the program graph. Threads are sometimes called *lightweight processes*. Modern operating systems, such as Unix, support the simultaneous execution of multiple processes. There need not be any actual parallelism. The operating system can interleave the execution of the processes. Within a single process, there can be multiple lightweight processes or threads, so there are two levels of multi-threading. Threads share a single address space, that of the parent process, allowing them to communicate through simple variables. There is no need for more complex, heavyweight inter-process communication mechanisms such as pipes.

Synchronization mechanisms are available to ensure that threads have exclusive access to shared data and cannot interfere with one another to corrupt shared data structures. Monitors and condition variables are available to synchronize the execution of threads. A monitor is

an object that can be locked and unlocked. Only one thread may hold the lock on a monitor. If a thread attempts to lock a monitor that is already locked by another thread, it is suspended until the monitor is unlocked. At that point it wakes up and tries again to lock the monitor. Condition variables allow threads to send signals to each other. Condition variables must be used in conjunction with a monitor; a thread must lock the associated monitor before using a condition variable.

The scheduler in the PN domain creates a thread for each node in the program graph. Each thread implements a dataflow process by repeatedly invoking the `run` method of a `Star` object. The scheduler itself does very little work, leaving the operating system to interleave the execution of threads. The `put` and `get` methods of the class `Geodesic` have been re-implemented using monitors and condition variables so that a thread attempting to read from an empty channel is automatically suspended, and threads automatically wake up when data becomes available.

The classes `PtThread`, `PtGate`, and `PtCondition` define the interfaces for threads, monitors, and condition variables in Ptolemy. Different implementations can be used as long as they conform to the interfaces defined in these base classes. At different points in the development of the PN domain, we experimented with implementations based on Sun's Lightweight Process library, AWESIME (A Widely Extensible Simulation Environment) by Dirk Grunwald [Gru91}, and Solaris threads [Pow91,Eyk92,Kha92,Kle92a,Kle92b,Ste92,Sun94]. The current implementation is based on a POSIX thread library by Frank Mueller [Mue92,Mue93,Gie93,Mue95]. This library, which runs on several platforms, is based on Draft 6 of the POSIX standard. Parts of our implementation will need to be updated to be compliant with the final POSIX thread standard.

By choosing the POSIX standard, we improve the portability of our code. Sun and Hewlett Packard already include an implementation of POSIX threads in their operating systems, Solaris 2.5 and HPUX 10. Having threads built into the kernel of the operating system, as opposed to a user library implementation, offers the opportunity for automatic parallelization on multiprocessor workstations. Thus, the same program runs properly on uniprocessor workstations and multiprocessor workstations without needing to be recompiled. This is important because it would be impractical to maintain different binary executables of Ptolemy for each workstation configuration.

10.2 Processes

Figure 10-1 shows the class derivation hierarchy for the classes that implement the

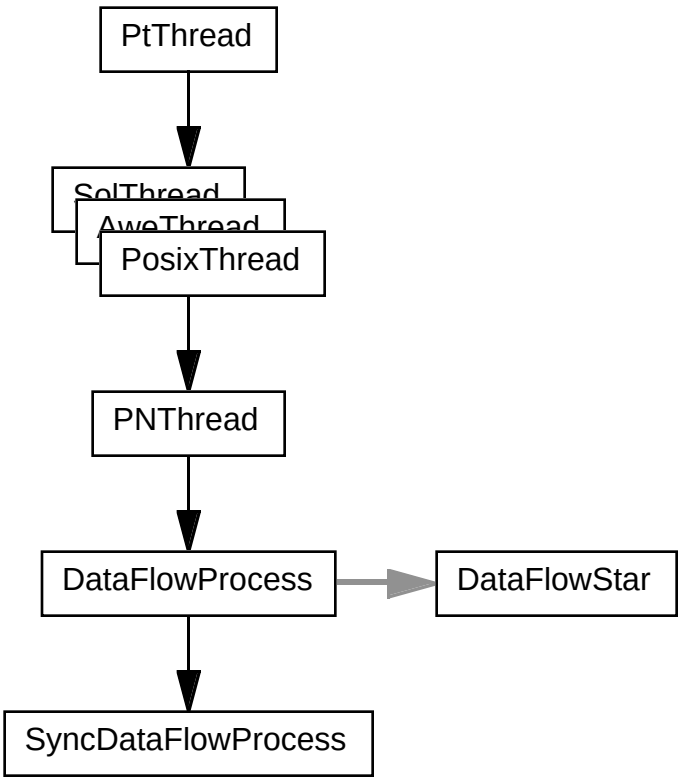

FIGURE 10-1: The class derivation hierarchy for threads. `PtThread` is an abstract base class with several possible implementations. Each `DataFlowProcess` refers to a `DataFlowStar`.

processes of Kahn process networks. The abstract base class `PtThread` defines the interface for threads in Ptolemy. The class `PosixThread` provides an implementation based on the POSIX thread standard. Other implementations using AWESIME [Gru91] or Solaris [Pow91] are possible. The class `PNThread` is a `typedef` that determines which implementation is used in the PN domain. Changing the underlying implementation simply requires changing this `typedef`. The class `DataFlowProcess`, which is derived from `PNThread`, implements a dataflow process. The `Star` object associated with an instance of `DataFlowProcess` is activated repeatedly, just as a dataflow actor is fired repeatedly to form a process.

10.2.1 The PtThread Class

`PtThread` is an abstract base class that defines the interface for all thread objects in Ptolemy. Because it has pure virtual methods, it is not possible to create an instance of `PtThread`. All of the methods are virtual so that objects can be referred to as a generic `PtThread`, but with the correct implementation-specific functionality.

The class `PtThread` has three public methods.

```
virtual void initialize() = 0;
```

This method initializes the thread and causes it to begin execution.

`virtual void runAll();`
: This method causes all threads to begin (or continue) execution.

`virtual void terminate() = 0;`
: This method causes execution of the thread to terminate.

The class `PtThread` has one protected method.

`virtual void run() = 0;`
: This method defines the functionality of the thread. It is invoked when the thread begins execution.

10.2.2 The PosixThread Class

The class `PosixThread` provides an implementation for the interface defined by `PtThread`. It does not implement the pure virtual method `run`, so it is not possible to create an instance of `PosixThread`. This class adds one protected method, and one protected data member to those already defined in `PtThread`.

`static void* runThis(PosixThread*);`
: This static method invokes the `run` method of the referenced thread. This provides a C interface that can be used by the POSIX thread library.

`pthread_t thread;`
: A handle for the POSIX thread associated with the `PosixThread` object.

`pthread_attr_t attributes;`
: A handle for the attributes associated with the POSIX thread.

`int detach;`
: A flag to set the detached state of the POSIX thread.

The `initialize` method shown below initializes attributes, then creates a thread. The thread is created in a non-detached state, which makes it possible to later synchronize with the thread as it terminates. The controlling thread (usually the main thread) invokes the `terminate` method of a thread and waits for it to terminate. The priority and scheduling policy for the thread are inherited from the thread that creates it, usually the main thread. A function pointer to the `runThis` method and the `this` pointer, which points to the current `PosixThread` object, are passed as arguments to the `pthread_create` function. This creates a thread that executes `runThis`, and passes `this` as an argument to `runThis`. Thus, the `run` method of the `PosixThread` object is the main function of the thread that is created. The `runThis` method is required because it would not be good practice to pass a function pointer to the `run` method as an argument to `pthread_create`. Although the `run` method has an implicit `this` pointer argument by virtue of the fact that it is a class method, this is really an implementation detail of the C++ compiler. By using the `runThis` method, we make the pointer argument explicit and avoid any dependencies on a particular compiler implementation.

```
void PosixThread::initialize()
{
```

```
        // Initialize attributes.
        pthread_attr_init(&attributes);

        // Detached threads free up their resources as soon
        // as they exit; non-detached threads can be joined.
        detach = 0;
        pthread_attr_setdetachstate(&attributes, &detach);

        // New threads inherit their priority and scheduling policy
        // from the current thread.
        pthread_attr_setinheritsched(&attributes,
                                     PTHREAD_INHERIT_SCHED);

        // Set the stack size to something reasonably large. (32K)
        pthread_attr_setstacksize(&attributes, 0x8000);

        // Create a thread.
        pthread_create(&thread, &attributes,
                        (pthread_func_t)runThis, this);
        // Discard temporary attribute object.
        pthread_attr_destroy(&attributes);
}
```

The `runAll` method, which is shown below, allows all threads to run by lowering the priority of the main thread. If execution of the threads ever stops, control returns to the main thread and its priority is raised again to prevent other threads from continuing.

```
// Start or continue the running of all threads.
void PosixThread::runAll()
{
        // Lower the priority to let other threads run. When control
        // returns, restore the priority of this thread to prevent
        // others from running.

        pthread_attr_t attributes;
        pthread_attr_init(&attributes);
        pthread_getschedattr(mainThread, &attributes);

        pthread_attr_setprio(&attributes, minPriority);
        pthread_setschedattr(mainThread, attributes);

        pthread_attr_setprio(&attributes, maxPriority);
        pthread_setschedattr(mainThread, attributes);

        pthread_attr_destroy(&attributes);
}
```

The `terminate` method shown below causes the thread to terminate before deleting the `PosixThread` object. First it requests that the thread associated with the `PosixThread` object terminate, using the `pthread_cancel` function. Then the current thread is suspended by `pthread_join` to give the cancelled thread an opportunity to terminate. Once termination

of that thread is complete, the current thread resumes and deallocates resources used by the terminated thread by calling `pthread_detach`. Thus one thread can cause another to terminate by invoking the `terminate` method of that thread.

```
void PosixThread::terminate()
{
      // Force the thread to terminate if it has not already done so.
      // Is it safe to do this to a thread that has already
      // terminated?
      pthread_cancel(thread);

      // Now wait.
      pthread_join(thread, NULL);
      pthread_detach(&thread);
}
```

10.2.3 The DataFlowProcess Class

The class `DataFlowProcess` is derived from `PosixThread`. It implements the *map* higher-order function (see the PN Domain chapter in the *User's Manua*l). A `DataFlowStar` is associated with each `DataFlowProcess` object.

`DataFlowStar& star;`
: This protected data member refers to the dataflow star associated with the `DataFlowProcess` object.

The constructor, shown below, initializes the `star` member to establish the association between the thread and the star.

```
DataFlowProcess(DataFlowStar& s)
      : star(s) {}
```

The `run` method, shown below, is defined to repeatedly invoke the `run` method of the star associated with the thread, just as the *map* function forms a process from repeated firings of a dataflow actor. Some dataflow stars in the BDF domain can operate with static scheduling or dynamic, run-time scheduling. Under static scheduling, a BDF star assumes that tokens are available on control inputs and appropriate data inputs. This requires that the scheduler be aware of the values of control tokens and the data ports that depend on these values. Because our scheduler has no such special knowledge, these stars must be properly configured for dynamic, multi-threaded execution in the PN domain. Stars in the BDF domain that have been configured for dynamic execution, and stars in the DDF domain dynamically inform the scheduler of data-dependent firing rules by designating a particular input `PortHole` with the `waitPort` method. Data must be retrieved from the designated input before invoking the star's `run` method. The star's `run` method is invoked repeatedly, until it indicates an error by returning `FALSE`.

```
void DataFlowProcess::run()
{
      // Configure the star for dynamic execution.
      star.setDynamicExecution(TRUE);
```

```
        // Fire the Star ad infinitum.
        do
        {
              if (star.waitPort()) star.waitPort()->receiveData();
        } while(star.run());
}
```

10.3 Communication Channels

Figure 10-2 shows the class derivation hierarchy for the classes that implement the

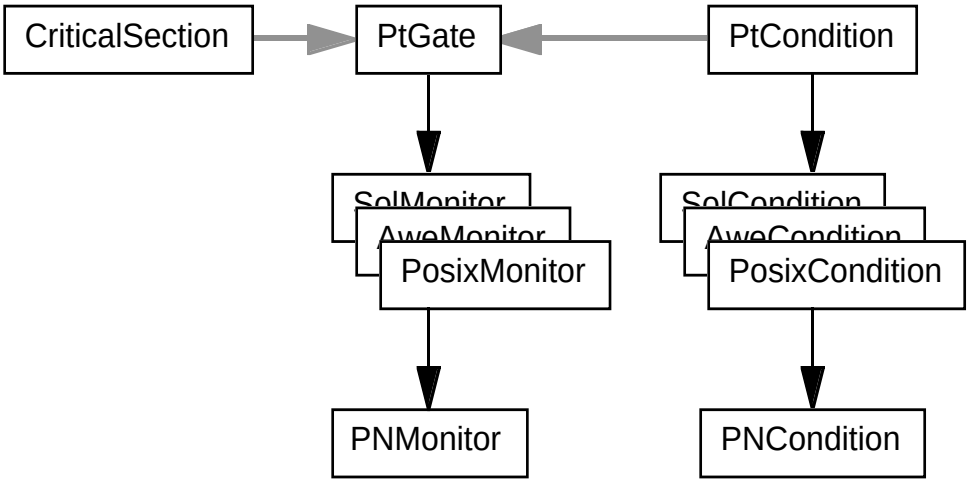

FIGURE 10-2: The class derivation hierarchy for monitors and condition variables. `PtGate` and `PtCondition` are abstract base classes, each with several possible implementations. Each `CriticalSection` and `PtCondition` refers to a `PtGate`.

communication channels of Kahn process networks. The classes that implement the communication channels provide the synchronization necessary to enforce the blocking read semantics of Kahn process networks. The classes `PtGate`, `PosixMonitor` and `CriticalSection` provide a mutual exclusion mechanism. The classes `PtCondition` and `PosixCondition` provide a synchronization mechanism. The class `PNGeodesic` uses these classes to implement a communication channel that enforces the blocking read operations of Kahn process networks and the blocking write operations required for bounded scheduling.

The abstract base class `PtGate` defines the interface for mutual exclusion objects in Ptolemy. The class `PosixMonitor` provides an implementation of `PtGate` based on the POSIX thread standard. Other implementations are possible. The class `PNMonitor` is a `typedef` that determines which implementation is used in the PN domain. Changing the underlying implementation simply requires changing this `typedef`.

The abstract base class `PtCondition` defines the interface for condition variables in Ptolemy. The class `PosixCondition` provides an implementation based on the POSIX thread standard. Other implementations are possible. The class `PNCondition` is a `typedef` that determines which implementation is used in the PN domain. Changing the underlying implementation simply requires changing this `typedef`.

The class `CriticalSection` provides a convenient method for manipulating

PtGate objects, preventing some common programming errors. The class PNGeodesic uses all of these classes to implement a communication channel.

10.3.1 PtGate

A PtGate can be locked and unlocked, but only one thread can hold the lock. Thus if a thread attempts to lock a PtGate that is already locked by another thread, it is suspended until the lock is released.

`virtual void lock() = 0;`
: This protected method locks the PtGate object for exclusive use by one thread.

`virtual void unlock() = 0;`
: This protected method releases the lock on the PtGate object.

10.3.2 PosixMonitor

The class PosixMonitor provides an implementation for the interface defined by PtGate. It has a single protected data member.

`pthread_mutex_t thread;`
: A handle for the POSIX monitor associated with the PosixMonitor object.

The implementations of the lock and unlock methods are shown below.

```
void PosixMonitor::lock()
{
      pthread_mutex_lock(&mutex);
}

void PosixMonitor::unlock()
{
      pthread_mutex_unlock(&mutex);
}
```

10.3.3 CriticalSection

The class CriticalSection provides a convenient mechanism for locking and unlocking PtGate objects. Its constructor, shown below, locks the gate. Its destructor, also shown below, unlocks the gate. To protect a section of code, simply create a new scope and declare an instance of CriticalSection. The PtGate is locked as soon as the CriticalSection is constructed. When execution of the code exits scope, the CriticalSection destructor is automatically invoked, unlocking the PtGate and preventing errors caused by forgetting to unlock it. Examples of this usage are shown in Section 10.3.6. Because only one thread can hold the lock on a PtGate, only one section of code guarded in this way can be active at a given time.

```
CriticalSection(PtGate* g) : mutex(g)
{
      if (mutex) mutex->lock();
```

```
}

~CriticalSection()
{
      if (mutex) mutex->unlock();
}
```

10.3.4 PtCondition

The class `PtCondition` defines the interface for condition variables in Ptolemy. A `PtCondition` provides synchronization through the `wait` and `notify` methods. A condition variable can be used only when executing code within a critical section (i.e., when a `PtGate` is locked).

`PtGate& mon;`
: This data member refers to the gate associated with the `PtCondition` object.

`virtual void wait() = 0;`
: This method suspends execution of the current thread until notification is received. The associated gate is unlocked before execution is suspended. Once notification is received, the lock on the gate is automatically reacquired before execution resumes.

`virtual void notify() = 0;`
: This method sends notification to one waiting thread. If multiple threads are waiting for notification, only one is activated.

`virtual void notifyAll() = 0;`
: This method sends notification to all waiting threads. If multiple threads are waiting for notification, all of them are activated. Once activated, all of the threads attempt to reacquire the lock on the gate, but only one of them succeeds. The others are suspended again until they can acquire the lock on the gate.

10.3.5 PosixCondition

The class `PosixCondition` provides an implementation for the interface defined by `PtCondition`. The implementations of the `wait`, `notify` and `notifyAll` methods are shown below.

```
void PosixCondition::wait()
{
      // Guarantee that the mutex will not remain locked
      // by a cancelled thread.
      pthread_cleanup_push((void(*)(void*))pthread_mutex_unlock,
            &mutex);

      pthread_cond_wait(&condition, &mutex);

      // Remove cleanup handler, but do not execute.
      pthread_cleanup_pop(FALSE);
```

```
}

void PosixCondition::notify()
{
      pthread_cond_signal(&condition);
}

void PosixCondition::notifyAll()
{
      pthread_cond_broadcast(&condition);
}
```

10.3.6 PNGeodesic

The class `PNGeodesic`, which is derived from the class `Geodesic` defined in the Ptolemy kernel, implements the communication channels for the PN domain. In conjunction with the `PtGate` member provided in the base class `Geodesic`, two condition variables provide the necessary synchronization for blocking read and blocking write operations.

`PtCondition* notEmpty;`
: This data member points to a condition variable used for blocking read operations when the channel is empty.

`PtCondition* notFull;`
: This data member points to a condition variable used for blocking write operations when the channel is full.

`int cap;`
: This data member represents the capacity of the communication channel and determines when it is full.

`static int numFull;`
: This static data member records the number of full geodesics in the system.

The `slowGet` method, shown in below, implements the get operation for communication channels. The entire method executes within a critical section to ensure consistency of the object's data members. If the buffer is empty, then the thread that invoked `slowGet` is suspended until notification is received on `notEmpty`. Data is retrieved from the buffer, and if it is not full notification is sent on `notFull` to any other thread that may have been waiting.

```
Particle* PNGeodesic::slowGet()
{
      // Avoid entering the gate more than once.
      CriticalSection region(gate);
      while (sz < 1 && notEmpty) notEmpty->wait();
      sz--;
      Particle* p = pstack.get();
      if (sz < cap && notFull) notFull->notifyAll();
      return p;
}
```

The `slowPut` method, shown below, implements the put operation for communication channels. The entire method executes within a critical section to ensure consistency of the object's data members. If the buffer is full, then the thread that invoked `slowPut` is suspended until notification is received on `notFull`. Data is placed in the buffer, and notification is sent on `notEmpty` to any other thread that may have been waiting.

```
// Block when full.
// Notify when not empty.
void PNGeodesic::slowPut(Particle* p)
{
      // Avoid entering the gate more than once.
      CriticalSection region(gate);
      if (sz >= cap && notFull)
      {
            {
                  CriticalSection region(fullGate);
                  numFull++;
            }
            while (sz >= cap && notFull) notFull->wait();
            {
                  CriticalSection region(fullGate);
                  numFull--;
            }
      }
      pstack.putTail(p); sz++;
      if (notEmpty) notEmpty->notifyAll();
}
```

The `setCapacity` method, shown below, is used to adjust the capacity limit of communication channels. If the capacity is increased so that a channel is no longer full, notification is sent on `notFull` to any thread that may have been waiting.

```
void PNGeodesic::setCapacity(int c)
{
      CriticalSection region(gate);
      cap = c;
      if (sz < cap && notFull) notFull->notifyAll();
}
```

10.4 Scheduling

Figure 10-3 shows the class derivation hierarchy for the classes that implement the

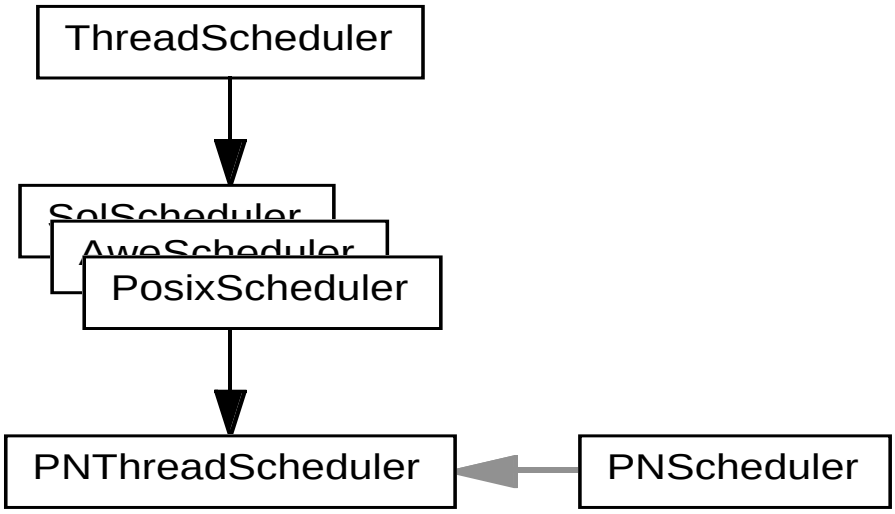

FIGURE 10-3: The class derivation hierarchy for schedulers. `ThreadList` is a container class for threads. Each `PNScheduler` uses a `ThreadList`.

dynamic scheduling of Kahn process networks. The class `ThreadList` provides mechanisms for terminating groups of threads. This class is used by `PNScheduler` to create threads for each node in the program graph. The class `SyncDataFlowProcess` implements the threads for the nodes.

10.4.1 ThreadList

The class `ThreadList` implements a container class for manipulating groups of threads. It has two public methods.

```
virtual void add(PtThread*);
```
This method adds a `PtThread` object to the list.

```
virtual ~ThreadScheduler();
```
This method terminates and deletes all threads in the list.

10.4.2 PNScheduler

The class `PNScheduler` controls the execution of a process network. Three data members support synchronization between the scheduler and the processes.

```
ThreadList* threads;
```
A container for the threads managed by the scheduler.

```
PNMonitor* monitor;
```
A monitor to guard the scheduler's condition variable.

```
PNCondition* start;
```
A condition variable for synchronizing with threads.

`int iteration;`
A counter for regulating the execution of the processes.

The `createThreads` method, shown below, creates one process for each node in the program graph. A `SyncDataFlowProcess` is created for each `DataFlowStar` and added to the `ThreadList` container.

```
// Create threads (dataflow processes).
void PNScheduler::createThreads()
{
	if (! galaxy()) return;
	GalStarIter nextStar(*galaxy());
	DataFlowStar* star;
	LOG_NEW; threads = new ThreadList;

	// Create Threads for all the Stars.
	while((star = (DataFlowStar*)nextStar++) != NULL)
	{
		LOG_NEW; SyncDataFlowProcess* p
			= new SyncDataFlowProcess(*star,*start,iteration);
		threads->add(p);
		p->initialize();
	}
}
```

It is often desirable to have a partial execution of a process network. The class `SyncDataFlowProcess`, which is derived from `DataFlowProcess`, supports this by synchronizing the execution of a thread with the `iteration` counter that belongs to the `PNScheduler`. The `run` methods of `PNScheduler` and `SyncDataFlowProcess` implement this synchronization. The `PNScheduler run` method, shown below, increments the `iteration` count to give every process an opportunity to run. The `SyncDataFlowProcess run` method, shown below, ensures that the number of invocations of the star's `run` method does not exceed the `iteration` count.

```
// Run (or continue) the simulation.
int PNScheduler::run()
{
	if (SimControl::haltRequested() || ! galaxy())
	{
		Error::abortRun("cannot continue");
		return FALSE;
	}

	while((currentTime < stopTime) && !SimControl::haltRequested())
	{
		// Notify all threads to continue.
		{
			CriticalSection region(start->monitor());
			iteration++;
			start->notifyAll();
		}
		PNThread::runAll();
```

```
                while (PNGeodesic::blockedOnFull() > 0
                        && !SimControl::haltRequested())
                {
                        increaseBuffers();
                        PNThread::runAll();
                }
                currentTime += schedulePeriod;
        }

        return !SimControl::haltRequested();
}

void SyncDataFlowProcess::run()
{
        int i = 0;
        // Configure the star for dynamic execution.
        star.setDynamicExecution(TRUE);

        // Fire the star ad infinitum.
        do
        {
                // Wait for notification to start.
                {
                        CriticalSection region(start.monitor());
                        while (iteration <= i) start.wait();
                        i = iteration;
                }
                if (star.waitPort()) star.waitPort()->receiveData();
        } while (star.run());
}
```

The `increaseBuffers` method is used during the course of execution to adjust the channel capacities according to the theory presented in [Par95, ch. 4]. Each time execution stops, the program graph is examined for full channels. If there are any full channels, then the capacity of the smallest one is increased.

```
// Increase buffer capacities.
// Return number of full buffers encountered.
int PNScheduler::increaseBuffers()
{
        int fullBuffers = 0;
        PNGeodesic* smallest = NULL;

        // Increase the capacity of the smallest full geodesic.
        GalStarIter nextStar(*galaxy());
        Star* star;
        while ((star = nextStar++) != NULL)
        {
                BlockPortIter nextPort(*star);
                PortHole* port;
                while ((port = nextPort++) != NULL)
                {
                        PNGeodesic* geo = NULL;
```

```
                        if (port->isItOutput() &&
                           (geo = (PNGeodesic*)port->geo()) != NULL)
                        {
                              if (geo->size() >= geo->capacity())
                              {
                                    fullBuffers++;
                                    if (smallest == NULL ||
                                        geo->capacity() <
                                          smallest->capacity())
                                          smallest = geo;
                              }
                        }
                  }
            }
            if (smallest != NULL)
                  smallest->setCapacity(smallest->capacity() + 1);

            return fullBuffers;
      }
```

10.5 Programming Stars in the PN Domain

Unlike portholes in the SDF domain, the number of tokens consumed by an input or produced by an output can be dynamic in the PN domain. This is indicated with the `P_DYNAMIC` porthhole attribute.

```
input {
      name { a }
      type { int }
      attributes { P_DYNAMIC }
}
```

For dynamic ports, it is necessary to invoke the `receiveData` and `sendData` methods explicitly. Note that the `receiveData` method must be used to initialize outputs. For static ports, the `receiveData` and `sendData` methods are invoked implicitly and should not be used in the go method.

Because a separate thread of execution is created for each star, the `go` method of a PN star is not required to terminate. As a programmer, you are free to use infinite loops, such as `while(TRUE) { ... }` within the `go` method of your PN stars. This may be necessary if you access a porthole (requiring a blocking read) before entering the main loop of the process. In the future, such code could be placed in the star's `begin` method, but currently (as of release 0.6) the `begin` method is executed before the star's thread is created.

```
go {
      // Read both inputs the first time.
      a.receiveData();
      b.receiveData();
      while (TRUE) {
            output.receiveData();// Initialize the output.
            if (int(a%0) < int(b%0)) {
```

```
                output%0 = a%0;
                output.sendData();
                a.receiveData();
            }
            else if (int(a%0) > int(b%0)) {
                output%0 = b%0;
                output.sendData();
                b.receiveData();
            }
            else {     // Remove duplicates.
                output%0 = a%0;
                output.sendData();
                a.receiveData();
                b.receiveData();
            }
        }
    }
```

Instead of using an infinite loop, most PN stars rely on the `run` method of `DataFlowProcess` to repeatedly invoke the star's `go` method.

Chapter 11. SR domain

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11.1 Introduction

Synchronous Reactive (SR) is a statically scheduled simulation domain in Ptolemy designed for concurrent, control-dominated systems. Simple stars for the SR domain are easy to write, but more complex ones that take full advantage of the domain are more subtle. Stars can be written in either C++ or Itcl.

11.2 Communication in SR

Time in SR is divided into discrete instants. In each instant, the communication channels in SR contain a valued event, have no event, or are "undefined," corresponding to when the system could not decide whether there was an event or not. These channels are not buffered, unlike Ptolemy's dataflow domains, and do not hold their values between instants.

Stars in the SR domain have input and output ports, much like they do in other domains. However, primarly because absent events are different from undefined ones, the interface to these ports are unique.

Because SR domain ports are unbuffered, output ports can be read just like input ports. It is often convenient to do this when checking to see whether the value on an output port is already correct and does not need to be changed.

Input/Output Porthole Interface

`int SRPortHole::known()`
: Return `TRUE` when the value in the port is is known.

`int SRPortHole::present()`
: Return `TRUE` when the value in the port is present.

`int SRPortHole::absent()`
: Return `TRUE` when the value in the port is absent.

`Particle & InSRPort::get()`
: Return the particle in the port. This should only be called when `present()` returns `TRUE`.

Output Porthole Interface

`Particle & OutSRPort::emit()`
: Force the value on the output port to be present and return a reference to the output particle.

`void OutSRPort::makeAbsent()`
Force the value on the output port to be absent.

11.3 Strict and non-strict SR stars

Broadly, there are two types of stars in the SR domain: strict and non-strict. If any input to a strict star is unknown, then all of its outputs are unknown. A two-input adder, for example, behaves like this--it cannot say anything about its output until the values of both inputs are known. A non-strict star, by contrast, can produce some outputs before all of its inputs are known. A two-input multiplexer is an example: when the selection input is known, it can ignore the unselected input.

Non-strict stars are the key to avoiding deadlocked situations when there are cyclic connections in the system. If all the stars in a cycle are strict, they each need all of their inputs before producing an output--all will be left waiting. The deadlock can be broken by introducing a non-strict star into the cycle that can produce an output without having all inputs from other stars in the cycle

A number of methods set attributes of SR stars. These should be called in the `setup()` method of a star as appropriate. By default, none of these attributes is assumed to hold.

`SRStar::reactive()`
Indicate the star is reactive--it needs at least one present input to produce a present output.

`Star::noInternalState()`
Indicate the star has no internal state--its behavior in an instant is a function only of the inputs in that instant, and not on history.

By default, a star in the SR domain is strict. Here is (abbreviated) `ptlang` source for a two-input adder:

```
defstar {
     name { Add }
     domain { SR }
    input {
         name { input1 }
         type { int }
     }
    input {
         name { input2 }
         type { int }
     }
    output {
         name { output }
         type { int }
     }
    setup {
         reactive();
```

```
            noInternalState();
        }
        go {
            if ( input1.present() && input2.present() ) {
                output.emit() <<
                    int(input1.get()) + int(input2.get());
            } else {
              Error::abortRun(*this,
                 "One input present, the other absent");
            }
        }
}
```

Non-strict stars inherit from the `SRNonStrictStar` class. Here is abbreviated source for a non-strict two-input multiplexer:

```
defstar {
     name { Mux }
     domain { SR }
     derivedFrom { SRNonStrictStar }
    input {
         name { trueInput }
         type { int }
     }
    input {
         name { falseInput }
         type { int }
     }
    input {
         name { select }
         type { int }
     }
    output {
         name { output }
         type { int }
     }
    setup {
         noInternalState();
         reactive();
     }
    go {
         if ( !output.known() && select.known() ) {
             if ( select.present() ) {
                 if ( int(select.get()) ) {
                    // Select is true--
                    // copy the true input if it's known
                    if ( trueInput.known() ) {
                         if ( trueInput.present() ) {
                             output.emit() <<
                              int(trueInput.get());
                         } else {
```

```
                                // true input is absent:
                                // make the output absent
                                output.makeAbsent();
                            }
                        }
                    } else {
                        // Select is false--
                        //copy the false input if it's known
                        if ( falseInput.known() ) {
                            if ( falseInput.present() ) {
                                output.emit() <<
                                   int(trueInput.get());
                            } else {
                                // false input is absent:
                                // make the output absent
                                output.makeAbsent();
                            }
                        }
                    }
                } else {
                    // Select is absent:
                    // make the output absent
                    output.makeAbsent();
                }
            }
        }
    }
```

Chapter 12. DE Domain

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12.1 Introduction

The discrete event (DE) domain in Ptolemy provides a general environment for time-oriented simulations of systems such as queueing networks, communication networks, and high-level computer architectures. In the domain, each `Particle` represents an *event* that corresponds to a change of the system state. The DE schedulers process events in chronological order. Since the time interval between events is generally not fixed, each particle has an associated *time-stamp*. Time stamps are generated by the block producing the particle, using the time stamps of the input particles and the latency of the block.

We assume in this chapter that the reader is thoroughly familiar with the DE model of computation. Refer to the *User's Manual*. Moreover, we assume the reader is familiar with chapter 2, "Writing Stars for Simulation". In this chapter, we give the additional information required to write stars for the DE domain.

12.2 Programming Stars in the DE Domain

A DE star can be viewed as an event-processor; it receives events from the outside, processes them, and generates output events after some latency. In a DE star, the management of the time stamps of the particles (events) is as important as the input/output mapping of particle values.

Generating output values and time stamps are separable tasks. For greatest modularity, therefore, we dedicate some DE stars, so-called *delay star*s, to time management. Examples of such stars are `Delay` and `Server`. These stars, when fired, produce output events that typically have larger time stamps than the input events. They usually do not manipulate the *value* of the particles in any interesting way. The other stars, so-called *functional star*s, avoid time-management, usually by generating output events with the same time stamp as the input events. They, however, *do* manipulate the *value* of the particles.

Delay stars should not be confused with the delay marker on an arc connecting two stars (represented in `pigi` by a small green diamond). The latter delay is not implemented as a star. It is a property of the arc. In the DE domain, the delay marker does not introduce a time delay, in the sense of an incremented time stamp. It simply tells the scheduler to ignore the arc while assigning dataflow-based firing priorities to stars. A star whose outputs are all marked with delays will have the lowest firing priority, and so will be fired last among those stars eligible to be fired at the current time.

The scheduler's assignment of firing priority also uses properties of the individual

stars: each star type can indicate whether or not it can produce zero-delay outputs. If a star indicates that it does not produce any output events with zero delay, then the scheduler can break the dataflow priority chain at that star. This saves the user from having to add explicit delay markers. A star class can make this indication either globally (it never produces any immediate output event) or on a port-by-port basis (only some of its input ports can produce immediate outputs, perhaps on only a subset of its output ports).

For managing time stamps, the `DEStar` class has two DE-specific members: `arrivalTime` and `completionTime`, summarized in table 12-1.. Before firing a star, a DE scheduler sets the value of the `arrivalTime` member to equal the time stamp of the event triggering the current firing. When the star fires, before returning, it typically sets the value of the `completionTime` member to the value of the time stamp of the latest event produced by the star. The schedulers do not use the `completionTime` member, however, so it can actually be used in any way the star writer wishes. `DEStar` also contains a field `delayType` and a method `setMode` that are used to signal the properties of the star, as described below.

12.2.1 Delay stars

*Delay-star*s manipulate time stamps. Two types of examples of delay stars are *pure delays*, and *servers*. A *pure-delay* star generates an output with the same value as the input sample, but with a time stamp that is greater than that of the input sample. The difference between the input sample time stamp and the output time stamp is a fixed, user-defined value. Consider for example the `Delay` star:

```
defstar {
	name {Delay}
	domain {DE}
	desc { Delays its input by a fixed amount }
	input {
		name {input}
		type {anytype}
	}
	output {
		name {output}
		type {=input}
	}
	defstate {
		name {delay}
		type {float}
		default {"1.0"}
		desc { Amount of time delay. }
	}
	constructor {
		delayType = TRUE;
	}
	go {
		completionTime = arrivalTime + double(delay);
		Particle& pp = input.get();
		output.put(completionTime) = pp;
	}
}
```

Inside the `go` method description, the `completionTime` is calculated by adding the delay to

the arrival time of the current event. The last two lines will be explained in more detail below.

Another type of delay star is a *server*. In a *server* star, the input event waits until a simulated resource becomes free to attend to it. An example is the `Server` star:

```
defstar {
      name {Server}
      domain {DE}
      desc {
This star emulates a server. If an input event arrives when it
is not busy, it delays it by the service time (a constant parameter).
If it arrives when it is busy, it delays it by more than the service
time. It must become free, and then serve the input.
      }
      input {
            name {input}
            type {anytype}
      }
      output {
            name {output}
            type {=input}
      }
      defstate {
            name {serviceTime}
            type {float}
            default {"1.0"}
            desc { Service time. }
      }
      constructor {
            delayType = TRUE;
      }
      go {
            // No overlapped execution. set the time.
            if (arrivalTime > completionTime)
                  completionTime = arrivalTime + double(serviceTime);
            else
                  completionTime += double(serviceTime);
            Particle& pp = input.get();
      output.put(completionTime) = pp;
      }
}
```

This star uses the `completionTime` member to store the time at which it becomes free after processing an input. On a given firing, if the `arrivalTime` is later than the `completionTime`, meaning that the input event has arrived when the server is free, then the server delays the input by the `serviceTime` only. Otherwise, the time stamp of the output event is calculated as the `serviceTime` plus the time at which the server becomes free (the `completionTime`).

Both pure delays and servers are delay stars. Hence their constructor sets the `delayType` member, summarized in table 12-1. This information is used by the scheduler.

The technical meaning of the `delayType` flag is this: such a star guarantees that it will never produce any output event with zero delay; all its output events will have timestamps

larger than the time of the firing in which they are emitted. Stars that can produce zero-delay events should leave `delayType` set to its default value of `FALSE`.

Actually, stars often cheat a little bit on this rule; as we just saw, the standard `Delay` star sets `delayType` even if the user sets the star's delay parameter to zero. This causes the star to be treated as though it had a positive delay for the purpose of assigning firing priorities, which is normally what is wanted. Both pure delays and servers are delay stars. Hence their constructor sets the `delayType` member, summarized in table 12-1. This information is used by the scheduler, and is particularly important when determining which of several simultaneous events to process first.

12.2.2 Functional Stars

In the DE model of computation, a star is *runnable* (ready for execution), if any input porthole has a new event, and that event has the smallest time stamp of any pending event in the system. When the star fires, it may need to know which input or inputs contain the events that triggered the firing. An input porthole containing a new particle has the `dataNew` flag set by the scheduler. The star can check the `dataNew` flag for each input. A functional star will typically read the value of the new input particles, compute the value of new output particles, and produce new output particles with time stamps identical to those of the new inputs. To see how this is done, consider the `Switch` star:

```
defstar {
      name {Switch}
      domain {DE}
      desc {
Switches input events to one of two outputs, depending on
the last received control input.
      }
      input {
            name {input}
            type {anytype}
      }
      input {
            name {control}
            type {int}
      }
      output {
            name {true}
            type {=input}
      }
      output {
            name {false}
            type {=input}
      }
      constructor {
            control.triggers();
            control.before(input);
      }
      go {
            if (input.dataNew) {
                  completionTime = arrivalTime;
```

```
                        Particle& pp = input.get();
                        int c = int(control%0);
                  if(c)
                              true.put(completionTime) = pp;
                        else
                              false.put(completionTime) = pp;
                  }
            }
      }
```

The `Switch` star has two input portholes: `input`, and `control`. When an event arrives at the `input` porthole, it routes the event to either the `true` or the `false` output porthole depending on the value of the last received `control` input. In the `go` method, we have to check whether a new `input` event has arrived. If not, then the firing was triggered by a `control` input event, and there is nothing to do. We simply return. If the `input` is new, then its particle is read using `get` method, as summarized in table 12-1. In addition, the most recent value from the control input is read. This value is used to determine which output should receive the data input. The statements in the constructor will be explained below in “Sequencing directives” on page 12-6.

There are three ways to access a particle from an input or output port. First, we may use the `%` operator followed by an integer, which is equivalent to the same operator in the SDF

InDEPort class

method	description
`Particle& operator %`	get a particle from the porthole without resetting dataNew
`void before (GenericPort& p)`	simultaneous inputs here should be processed before those at p
`int dataNew`	flag indicating whether the porthole has new data
`Particle& get ()`	get a particle from the porthole and reset dataNew
`void getSimulEvent ()`	fetch a simultaneous event from the global event queue
`int numSimulEvents ()`	return the number of pending simultaneous events at this input
`void triggers ()`	indicate that the input does not trigger any immediate output events
`void triggers (GenericPort& p)`	indicate that the input triggers an immediate output on port p

OutDEPort class

	description
`Particle& operator %`	get the most recent particle from the porthole
`Particle& put (double time)`	get a new writable particle with the given time stamp
`void sendData ()`	flush output porthole data to the global event queue (called by put)

TABLE 12-1: A summary of the members and methods of the `InDEPort` and `OutDEPort` classes that are used by star writers.

domain. For example, `control%0` returns the most recent particle from the `control` porthole. The second method, `get`, is specific to `InDEPort`. It resets the `dataNew` member of the port as well as returning the most recent particle from an input port. In the above example, we are not using the `dataNew` flag for the `control` input, so there is no need to reset it. However, we are using it for the `input` porthole, so it must be reset. If you need to reset the `dataNew` member of a input port after reading the newly arrived event (the more common case) you should use the `get` method instead of `%0` operator. Alternatively, you can reset the `dataNew` flag explicitly using a statement like:

```
input.dataNew = FALSE;
```

The `put` method is also specific to `OutDEPort`. It sets the `timeStamp` member of the port to the value given by its argument, and returns a reference to the most recent particle from an output port. Consider the line in the above example:

```
true.put(completionTime) = pp;
```

This says that we copy the particle `pp` to the output port with `timeStamp = completionTime`. We can send more than one output event to the same port by calling the `put` method repeatedly. A new particle is returned each time.

12.2.3 Sequencing directives

A special effort has been made in the DE domain to handle simultaneous events in a rational way. If two distinct stars can be fired because they both have events at their inputs with identical time stamps, some choice must be made as to which one to fire. A common strategy is to choose one arbitrarily. This scheme has the simplest implementation, but can lead to unexpected and counterintuitive results from a simulation.

The choice of which to fire is made in Ptolemy by statically assigning priorities to the stars according to a topological sort. Thus, if one of the two enabled stars could produce events with zero delay that would affect the other, as shown in figure 12-1, then that star will be fired first. The topological sort is actually even more sophisticated than we have indicated. It follows triggering relationships between input and output portholes selectively, according to assertions made in the star definition. Thus, the priorities are actually assigned to individual portholes, rather than to entire stars.

The cryptic statements in the constructor in the above example reveal these triggering relationships to the scheduler. Consider for example the following problem. In the `Switch` star above suppose that on a given firing, an `input` with time stamp τ is processed, and the particle is sent to the `true` output. Suppose that the very next time the star fires, a `control`

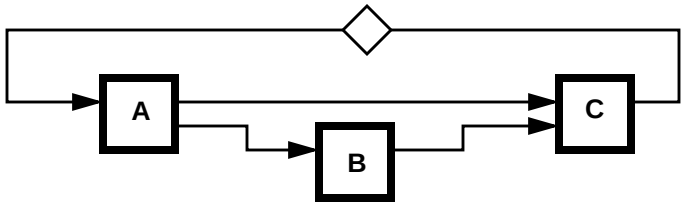

FIGURE 12-1: When DE stars are enabled by simultaneous events, the choice of which to fire is determined by priorities based on a topological sort. Thus if B and C both have events with identical time stamps, B will take priority over C. The delay on the path from C to A serves to break the topological sort.

input with time stamp τ arrives with value FALSE. Probably, the previous output should have gone to the false porthole. Consider the constructor statement:

```
control.before(input);
```

This tells the scheduler that if a situation arises where two simultaneous events might appear at the control and input portholes, then the one at the control porthole should appear first. This is implemented by giving the stars "upstream" from the control porthole higher firing priorities than those "upstream" from the input porthole. Thus, if for some reason the simultaneous events are processed in two separate firings (always a possibility), then the control event is sure to be processed first. A chain of before directives can assign relative priorities to a whole set of inputs.

The other statement in the constructor:

```
control.triggers();
```

has somewhat different objectives. It tells the scheduler that a control input does not trigger outputs on any porthole. If an input event causes an output event with the same time stamp, then the input event is said to have "triggered" the output event. In the above example, the control event does not trigger any immediate output event, but an input event does. By default, an input triggers all outputs, so it is not necessary to add the directive

```
input.triggers(output);
```

Providing triggers directives informs the scheduler that certain paths through the graph do not have zero delay, allowing it to ignore those paths in making its topological sort. The triggers directive is essentially a selective version of the delayType flag: setting delayType means the star contains **no** zero-delay paths, whereas providing triggers information tells the scheduler that only certain porthole-to-porthole paths through the star have zero delay. By default, the scheduler assumes that all paths through the star have zero delay.

In some stars, an input event conditionally triggers an output. In principle, if there is any chance of triggering an output, we set the triggering relation between the input and the output. The triggering relation informs the scheduler that there **may be** a delay-free path from the input to the output. It is important, therefore, that the star writer not miss any triggering relation when triggers directives are provided.

If an input triggers some, but not all outputs, then the constructor for the star should contain several triggers directives, one for each output that is triggered by that input. If an input triggers all outputs, then no directive is necessary for it.

If delayType is set to TRUE, it is not necessary to write any triggers directives; a delay star by definition never triggers zero-delay output events.

12.2.4 Simultaneous events

An input port may have a sequence of simultaneous events (events with identical time stamps) pending. Normally, the star will be fired repeatedly until all such events have been consumed. Optionally, a DE star may process simultaneous events during a single firing. The getSimulEvent method can be used as in the following example, taken from an up-down counter star:

```
go {
...   while (countUp.dataNew) {
            count++;
            countUp.getSimulEvent();
```

```
}
... }
```

Here, `countUp` is an input porthole. The `getSimulEvent` method examines the global event queue to see if any more events are available for the porthole with the current timestamp. If so, it fetches the next one and sets the `dataNew` flag to `TRUE`; if none remain, it sets the `dataNew` flag to `FALSE`. (In this example, the actual values of the input events are uninteresting, but the star could use `get()` within the loop if it did need the event values.)

Sometimes, a star simply needs to know how many simultaneous events are pending on a given porthole. Without fetching any event, we can get the number of simultaneous events by calling the `numSimulEvents` method. This returns the number of simultaneous events still waiting in the global event queue; the one already in the porthole isn't counted.

If the star has multiple input ports, the programmer should carefully consider the desired behavior of simultaneous inputs on different ports, and choose the order of processing of events accordingly. For example, it might be appropriate to absorb all the events available for a control porthole before examining any events for a data porthole.

If a star will always absorb all simultaneous events for all its input portholes, it can use phase-based firing mode to improve performance. See section 12.3.

12.2.5 Non-deterministic loops

The handling of simultaneous events is based on assigning priorities to portholes, tracing the connectivity of a schematic, and using the relationships established by the `before` and `triggers` relationships. When we assign these priorities, we start from the input ports of sink stars, and rely primarily on a topological sort. Delay-free loops, which would prevent the topological sort for terminating, are detected and ruled out. But, another kind of loop, called a *non-deterministic loop*, can cause unexpected results. A non-deterministic loop is one in which the priorities cannot be assigned uniquely; there is more than one solution. Such a loop has at least one `before` relation. If a programmer can guarantee that there is no possibility of simultaneous events on such a loop, then system may be simulated in a predictable manner. Otherwise, the arbitrary decisions in the scheduler will affect the firing order.

If a non-deterministic loop contains exactly one `before` relation, the scheduler assigns priorities in a well-defined way, but unfortunately, in a way that is hidden from the user. For a non-deterministic loop with more than one `before` relation, the assignment of the priorities is a non-deterministic procedure. Therefore, the scheduler emits a warning message. The warning message suggests that the programmer put a delay element on an arc (usually a feedback arc) to break the non-deterministic loop. As mentioned before, the delay element has a totally different meaning from that in the SDF domain. In the SDF domain, a delay implies an initial token on the arc, implying a one-sample delay. In the DE domain, however, a delay element simply breaks a triggering chain. Therefore, the source port of the arc is assigned the lowest priority.

12.2.6 Source stars

The DE stars discussed so far fire in response to input events. In order to build signal generators, or source stars, or stars with outputs but no inputs, we need another class of DE star, called a *self-scheduling star.* A self-scheduling star fools the scheduler by generating its own input events. These feedback events trigger the star firings. An event generator is a spe-

cial case of a delay star, in that its role is mainly to control the time spacing of source events. The values of the source events can be determined by a functional block attached to the output of the event generator (e.g. `Const`, `Ramp`, etc).

A self-scheduling star is derived from class `DERepeatStar`, which in turn is derived from class `DEStar`. The `DERepeatStar` class has two special methods to facilitate the self-scheduling function: `refireAtTime` and `canGetFired`. These are summarized in table 12-2. The `Poisson` star illustrates these:

```
defstar {
      name {Poisson}
      domain {DE}
      derivedfrom { RepeatStar }
      desc {
Generates events according to a Poisson process.
The first event comes out at time zero.
      }
      output {
            name {output}
            type {float}
      }
      defstate {
            name {meanTime}
            type {float}
            default {"1.0"}
            desc { The mean inter-arrival time. }
      }
      defstate {
            name {magnitude}
            type {float}
            default {"1.0"}
            desc { The value of outputs generated. }
      }
      hinclude { <NegExp.h> }
      ccinclude { <ACG.h> }
      protected {
            NegativeExpntl *random;
      }
      // declare the static random-number generator in the .cc file
```

DERepeatStar class

method	description
`int canGetFired ( )`	return 1 if the star is enabled for firing
`void refireAtTime (double t)`	schedule the star to fire again at time t
`void begin ()`	schedule the star to fire at time zero

TABLE 12-2: A summary of the methods of the `DERepeatStar` class used when writing a source star. Source stars are derived from this.

```
        code {
              extern ACG* gen;
        }
        constructor {
              random = NULL;
        }
        destructor {
              if(random) delete random;
        }
        begin {
              if(random) delete random;
              random = new NegativeExpntl(double(meanTime),gen);
              DERepeatStar::begin ();
        }
        go {
              // Generate an output event
              // (Recall that the first event comes out at time 0).
              output.put(completionTime) << double(magnitude);

              // and schedule the next firing
              refireAtTime(completionTime);

              // Generate an exponential random variable.
              double p = (*random)();

              // Turn it into an exponential, and add to completionTime
              completionTime += p;
        }
}
```

The `Poisson` star generates a Poisson process. The inter-arrival time of events is exponentially distributed with parameter *meanTime*. Refer to “Using Random Numbers” on page 3-17 for information about the random number generation. The method `refireAtTime` launches an event onto a feedback arc that is invisible to the users. The feedback event triggers the self-scheduling star some time later.

Note that the feedback event for the next execution is generated in the current execution. To initiate this process, an event is placed on the feedback arc by the `DERepeatStar::begin` method, before the scheduler runs.

The `DERepeatStar` class can also be used for other purposes besides event generation. For example, a sampler star might be written to fire itself at regular intervals using the `refireAtTime` method.

Another strangely named method, `canGetFired` is seldom used in the star definitions. The method checks for the existence of a new feedback event, and returns `TRUE` if it is there, or `FALSE` otherwise.

The internal feedback arc consists of an input and an output porthole that are automatically created and connected together, with a delay marker added to prevent the scheduler from complaining about a delay-free loop. (This effectively assumes that refire requests will always be for times greater than the current time.)

Sometimes the programmer of a star derived from `DERepeatStar` needs to be explic-

itly aware of these portholes. In particular, they should be taken into account when considering whether a star is delay-type. Setting `delayType` in a `DERepeatStar` derivative asserts that not only do none of the star's visible input portholes trigger output events with zero delay, but refire events do not either. Frequently this is a false statement. It's usually safer to write `triggers` directives that indicate that specific input portholes cannot trigger zero-delay outputs. (Since the feedback portholes have a delay marker, it is never necessary to mention the feedback output porthole in `triggers` directives, even for an input porthole that gives rise to `refireAtTime` requests --- the scheduler is uninterested in zero-delay paths to the feedback output.)

The event passed across the feedback arc is an ordinary FLOAT particle, normally having value zero. Sometimes it can be useful to store extra information in the feedback event. Beginning in Ptolemy 0.7, the `refireAtTime` method accepts an optional second parameter that gives the numeric value to place in the feedback event. Fetching the value currently requires direct access to the feedback input port, for example

```
if (feedbackIn->dataNew) {
      double feedbackValue = double(feedbackIn->get());
      ...
```

A future version of `DERepeatStar` might provide some syntactic sugar to hide the details of this operation.

In Ptolemy versions prior to 0.7, `DERepeatStar` did not place a delay marker on the feedback arc, but instead used a hack involving special porthole priorities. This hack did not behave very well if the star also had ordinary input portholes. To work around it, writers of derived star types would sometimes set `delayType` or provide `triggers` directives. When updating such stars to 0.7, these statements should be examined critically --- they will often be found to be unnecessary, and perhaps even wrong.

12.3 Phase-Based Firing Mode

The ordering of simultaneous events is the most challenging task of the DE scheduler. In general, simultaneous events are caused by insufficient time resolution, particularly when the time unit is integral. In our case, simultaneous events are primarily caused by functional stars that produce output events with the same time stamp as the input events. Since the time stamp is a double-precision floating-point number, we have very high time resolution.

As explained earlier, the DE scheduler fetches at most one event for each input porthole for each firing of a DE star. In the body of the star code, the programmer can consume the simultaneous events onto a certain input porthole by calling the `getSimulEvent` method for the porthole. This mode of operation is called *simple* mode, which is the default mode of operation.

Suppose we program a new DE star, called `Counter`. The `Counter` star has one `clock` input and one `demand` input. A `clock` event will increase the counter value by one, and the `demand` input will send the counter value to the output. If there are multiple simultaneous `clock` inputs and a simultaneous `demand` input, we should count all the `clock` inputs before consuming the `demand` input and producing an output. Thus, the programmer should call the `getSimulEvent` method for the `clock` input. However, the `getSimulEvent` method is expensive when there are many simultaneous events, since it gets only one simulta-

neous event at a time. This runtime overhead is reduced in the *phase-based firing* mode.

In the *phase-based firing* mode, or simply the *phase* mode, before executing a star, the scheduler fetches all simultaneous events for the star. The fetched events are stored in the internal queue of each input porthole. The internal queue of inputs is created only if the star operates in phase mode. In phase mode, when a DE star fires, it consumes all simultaneous events currently available. It constructs a *phase*. Afterwards, other simultaneous events for the same star may be generated by a network of functional stars. Then, the star may be fired again with another set of simultaneous events, which forms another phase. We can set the operation mode of a star *phase* by calling method `setMode(PHASE)` in the constructor, as summarized in table 12-1 on page 12-5. The following example is written in the simple mode.

```
go {
        ...
        while (input.dataNew) {
                temp += int(input.get());
                input.getSimulEvent();
        }
        ...
}
```

If the star is re-written using the phase mode, it will look like:

```
constructor {
        setMode(PHASE);
}
go {
        ...
        while (input.dataNew) {
                temp += int(input.get());
        }
        ...
}
```

or,

```
go {
        ...
        for (int i = input.numSimulEvents(); i > 0; i--) {
                temp += int(input.get());
        }
        ...
}
```

The `get` method in phase mode fetches events from the internal queue one at a time. After consuming all events from the queue (now the queue is empty), it resets the `dataNew` flag. If a star in phase mode does not access all simultaneous input events in a particular firing, the unaccessed events are discarded.

The method, `numSimulEvent`, returns the current queue size in phase mode. Recall that in simple mode, the method returns the number of simultaneous events in the global event queue, which is one less than the actual number of simultaneous events. This difference of one between two modes is necessary for coding efficiency.

There is still inherent non-determinism in the handling of simultaneous events in the

DE domain. For example, suppose that the `Switch` star has more than one simultaneous control event. Which one is really the last one? Since the input is routed to either the `true` or `false` output depending on the last value of the `control` event, the decision is quite critical. We leave the responsibility of resolving such inherent non-determinism to the user.

12.4 Programming Examples

This section presents different examples of programming in the discrete-event domain. There are no pre-defined stars that work with matrices in the discrete-event domain. We will give several examples of DE stars that work with matrices.

12.4.1 Identity Matrix Star

This section develops a star in the DE domain that will create an identity matrix. Instead of creating a source star which must schedule itself, we will create a star that fires whenever it receives an new input value. For example, a clock or some other source can be attached to the star to set its firing pattern.

```
defstar {
      name { Identity_M }
      domain { DE }
      desc { Output a floating-point identity matrix.}
      author { Brian L. Evans }
      input {
            name { input }
            type { anytype }
      }
      output {
            name { output }
            type { FLOAT_MATRIX_ENV }
      }
      defstate {
            name { rowsCols }
            type { int }
            default { 2 }
            desc {
Number of rows and columns of the output square matrix. }
      }
      ccinclude { "Matrix.h" }
      go {
            // Functional Star: pass timestamp without change
            completionTime = arrivalTime;
            // For messages, you must pass dynamically allocated data
            FloatMatrix& result =
                  *(new FloatMatrix(int(rowsCols),int(rowsCols)));
            // Set the contents of the matrix to an identity matrix
            result.identity();
            // Send the matrix result to the output port
            output.put(completionTime) << result;
            }
      }
```

This is a functional star because the time stamp on the input particle is not altered. The output is a matrix message. The matrix is a square matrix. In order for the matrix to remain defined after the go method finishes, the matrix `result` cannot be allocated from local memory. Instead, it must be allocated from global dynamic memory via the `new` operator. In the syntax for the new operator, the `int` cast in `int(rowsCols)` extracts the value from `rowsCols` which is an instance of the `State` data structure. The dynamic memory allocated for the matrix will be automatically deleted by the `Message` class. Then, the matrix is reset to be an identity matrix. Finally, the matrix is sent to the output port with the same time stamp as that of the input data. Note that the syntax to output data in the discrete-event domain differs from the syntax of the synchronous dataflow domain due to the time stamp. In the SDF domain, the output code would be

```
output%0 << result
```

12.4.2 Matrix Transpose

In the next example, we will compute the matrix transpose.

```
defstar {
	name { Transpose_M }
	domain { DE }
	desc { Transpose a floating-point matrix.}
	author { Brian L. Evans }
	input {
		name { input }
		type { FLOAT_MATRIX_ENV }
	}
	output {
		name { output }
		type { FLOAT_MATRIX_ENV }
	}
	ccinclude { "Matrix.h" }
	go {
		// Functional Star: pass timestamp without change
		completionTime = arrivalTime;
		// Extract the matrix on the input port
		Envelope Xpkt;
		input.get().getMessage(Xpkt);
		const FloatMatrix& Xmatrix =
			*(const FloatMatrix *)Xpkt.myData();
		// Create a copy of the input matrix
		FloatMatrix& xtrans = *(new FloatMatrix(Xmatrix));
		// Transpose the matrix
		xtrans.transpose();
		// Send the matrix result to the output port
		output.put(completionTime) << xtrans;
	}
}
```

The key difference between creating an identity matrix and taking a matrix transpose in the DE domain is the conversion of the input data to a matrix. The input data comes in the

form of an envelope which is essentially an instance of a class embedded in a message particle. To extract the contents of the message, we first extract the message from the input envelope. Then, we extract the data field from the message and cast it to be a `FloatMatrix`. Just as in the previous example, we need to allocate dynamic memory to hold the value of the matrix to be output. In this case, we do not have to code the transpose operation since it is already built into the matrix classes.

Chapter 13. Code Generation

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13.1 Introduction

The CG domain and derivative domains are used to generate code rather than to run simulations [Pin92]. Only the derivative domains are of practical use for generating code. The stars in the CG domain can be thought of as "comment generators"; they are useful for testing and debugging schedulers and for little else. The CG domain is intended as a model and a collection of base classes for derivative domains. This section documents the common features and general structure of all code generation domains.

The CG domain is currently based on dataflow semantics. Dataflow models of computation in Ptolemy include synchronous dataflow (SDF), dynamic dataflow (DDF), and boolean dataflow (BDF). Both DDF and BDF are very general models of dataflow in that they are Turing equivalent. SDF is a subset of both these models. Hence, a code generation target that uses the BDF scheduler can support BDF and SDF stars but a target that uses SDF schedulers only supports SDF stars. Most targets in code generation domains use SDF schedulers and parallel schedulers which makes these targets support only SDF stars. An advantage of SDF is that compilation can be done statically; this permits very efficient code generation. While we have implemented targets that allow DDF code generation stars in the system, these targets are not in the current release. However, there are a couple of targets that use the BDF scheduler; refer to the BDF domain documentation, the section on the bdf-cg target in the CG domain documentation in the user's manual, and the section on the bdf-cgc target in the CGC domain documentation for more information on BDF semantics and the types of stars that can be supported. In this chapter, we assume that stars obey only SDF semantics since code generation for non-SDF models is still in its early stages.

The design goal of the code generation class hierarchy is to save work and to make the system more maintainable. Most of the work required to allocate memory for buffers, constants, tables, and to generate symbols that are required in code is completely processor-independent; hence these facilities are provided in the generic classes found in the `$PTOLEMY/src/domains/cg/kernel` directory.

A key feature of code generation domains is the notion of a target architecture. Every application must have a user-specified target architecture, selected from a set of targets supported by the user-selected domain. Every target architecture is derived from the base class `Target`, and controls such operations as scheduling, compiling, assembling, and downloading code. Since it controls scheduling, multiprocessor architectures can be supported with

automated task partitioning and synchronization.

In the following sections, we will introduce the methods and data structures needed to write new code generation stars and targets. However, we will not document what is needed to write a new code generation domain; that discussion can be found in chapter 17. We will first introduce what is needed to write a new code generation star, introducing the concepts of *code blocks*, *code streams* and *code block macros*. Next we will describe the various methods which will generally use the `addCode` method to piece together the code blocks into the code streams. We will then go into what is required to write single-processor and multiple-processor targets. Finally we will document the various schedulers available in the code generation domains.

13.2 Writing Code Generation Stars

Code generation stars are very similar to the C++ simulation stars. The main difference is that the initialization (`setup()`), run time (`go()`), and termination (`wrapup()`) methods generate code to be compiled and executed later. Additionally, code generation stars have two more methods called `initCode()`and `execTime()`.

The `setup()` method is called before the schedule is generated and before any memory is allocated. In this method, we usually initialize local variables or states. Note that the setup method of a star may be called multiple times. This means that the user should be careful so that the behavior of the star does not change even though setup method is called multiple times. The `initCode()` method of a star is called after the static schedule has been generated and before the schedule is fired. This method is used to generate the code outside of the main loop such as initialization code and procedure declaration code. To generate start-up code, use the `initCode` method, NOT the setup method, since setup is called before scheduling and memory allocation. The main use of the setup method, as in SDF, is to tell the scheduler if more than one sample is to be accessed from a porthole with the `setSDFParams` call.

The `go()` function is used to generate the main loop code for the star. Finally, the `wrapup()` function is used to generate the code after the main loop.

The `execTime()` method returns an integer specifying the time needed to execute the main loop code of a code generation star in processor cycles or instruction steps. These numbers are used by the parallel schedulers. In the assembly code generation domains, the integer returned is the main loop code execution time in DSP instruction cycles. The better the `execTime()` estimates are for each star, the more efficient the parallel schedule becomes.

If a star is invoked more than once during an iteration period, the precedence relation between stars should be known to the parallel scheduler. If there is no precedence relation between invocations, the parallel scheduler will try to parallelize them. By default, there is a precedence relation between invocations for any star (this is equivalent to having a self-loop). To assert that there is no such self-loop for a star, we have to call the `noInternalState()` method in the constructor:

```
constructor {
     noInternalState();
}
```

It is strongly recommended that the star designer determine whether the star is parallelizable or not, and call `noInternalState()` if it is.

The CGStar class is the base class for all code generation stars, such as high level language code generation stars and assembly language code generation stars. In this section, we will explain the common features that the CGStar class provides for all derivative code generation stars.

As a simple example to see how code generation stars are written, let's write an adder star for the C code generation domain. The defstar is almost the same as for a simulation star:

```
defstar {
     name {Add}
     domain {CGC}
     desc { Output the sum of the inputs, as a floating
value.}
     author { J. Pino }
     input {
          name {input1}
          type {float}
     }
     input {
          name {input2}
          type {float}
     }
     output {
          name {output}
          type {float}
     }
     ...
```

13.2.1 Codeblocks

Next we have to define the C code which will be used to generate the run-time code. For this we use a codeblock. A codeblock is a pseudo-language specification of a code segment. By pseudo-language we mean that the block of code is written in the target language with interspersed macros. Macros will be explained in the following section.

Codeblocks are implemented as protected static class members (e.g. there is one instance of a codeblock for the entire class). Since they are protected, codeblocks from one star class can be used from a derived star. The codeblock directive defines a block of code with an associated identifying name ("addCB" in this case).

```
codeblock (addCB) {
/* output = input1 + input2 */
$ref(output) = $ref(input1) + $ref(input2);
}
```

Special care should be given to codeblock specification. Within each line, spaces, tabs, and new line characters are important because they are preserved. For this reason, the brackets "{ }" should not be on the same lines with the code. Had addCB been defined as follows:

```
codeblock (addCB) { /* output = input1 + input2 */
$ref(output) = $ref(input1) + $ref(input2); }
```

the line

```
ref(output) = $ref(input1) + $ref(input2);
```

would be lost! This is because anything preceding the closing "}" on the same line is discarded by the preprocessor (ptlang). Secondly, the spaces and tabs between the opening "{" and the first non-space character will be ignored.

The first definition of the addCB codeblock is translated by ptlang into a definition of a static public member in the .h file:

```
class CGCAdd : public CGCStar
{
...
static CodeBlock addCB;
...
}
```

An associated constructor call will be generated in the .cc file:

```
CodeBlock CGCAdd :: addCB (
" /* output = input1 + input2 */\n"
" $ref(output) = $ref(input1) + $ref(input2);\n"
);
```

The argument is a single string, divided into lines for convenience. The following will complete our definition of the add star:

```
go {
      addCode(addCB);
}
```

Notice that the code is added in the go method, thus implying that the code is generated in the main loop.

The

```
addCode(code,stream name,<unique name>)
```

method of a CG star provides an interface to all the code streams (stream name and unique-name arguments are optional). This method defaults to adding code into the myCode stream (codestreams are explained later on). If a stream name is specified, addCode looks up the stream using the getStream(*stream-name*) method and then adds the code into that stream. Furthermore, if a unique name is provided for the code, the code will only be added if no other code has previously been added with the given unique name. The method addCode will return TRUE if the code-string has been added to the stream and otherwise will return FALSE.

The star just defined is a very simple star. Typical code generation stars will define many codeblocks. Conditional code generation is easily accomplished, as is done in the following example:

```
go {
      if (parameter == YES)
            addCode(yesblock);
      else
            addCode(noblock);
```

```
}
```

So far, we have used the `addCode()` method to generate the code inside the main loop body. In the assembly language domains, `addCode` can be called in the `initCode` and `wrapup` methods, to place code before or after the main loop respectively. In all of the code generation domains, we can use the `addProcedure()` method to generate declarations outside of the main body. Refer to "Code streams" on page 13-16 for documentation on the `addCode` and `addProcedure` methods.

The next section describes the extended codeblock support. The previous discussion of simple codeblocks is still correct and supported by `ptlang`; the extensions below are upward compatible. These extensions are experimental. They may change in future version of Ptolemy, and may still contain bugs.

13.2.2 Codeblocks with arguments

Simple codeblocks (as described above) have a name and are implemented as static member strings. Extended codeblocks have a name, optional arguments, and are implemented as non-static functions. They have an escape mechanism so that C++ expressions may be evaluated at run time and inserted into the generated code. However, in order to take advantage of this escape mechanism, a codeblock must be defined and called with arguments, even if those arguments are empty. An example:

```
codeblock(cbLoop,"int N, double x") {
      for (i=0; i < @N; i++) {
          $ref(output,i) = sin(i*@x);
      }
}
```

This defines a codeblock named `cbLoop` with two arguments: *`N`* and *`x`*. The variable *`i`* will appear in the generated code, while the C++ expressions *`N`* and *`x`* are escaped by `@` and will be evaluated at code-generation time. When this is called as

```
cbLoop(5, 0.1);
```

the following string will be returned:

```
      for (i=0; i < 5; i++) {
          $ref(output,i) = sin(i*0.1);
      }
```

This might be used within a `go()` method as:

```
go {
      addCode(cbLoop(5, 0.1));
}
```

The `addCode()` method will process the `$ref()` macro as described elsewhere. More complicated expressions are allowable. In general, the `@` clause may be delimited by parentheses "`(`"and "`)`", and must be operator << printable. The above codeblock could have been equivalently declared as:

```
    codeblock(cbLoop,"int N, double x") {
      for (i=0; i < @(N); i++) {
          $ref(output,i) = sin(i*@(x));
      }
}
```

A more complicated example follows:

```
codeblock(cbLoop2,"char *portname, int N, double x") {
      for (i=0; i < @(int(length)); i++) {
          $ref(@portname,i) = sin(i*@(x/N));
      }
}
```

In this example, *length* is a data member of the star (typically a state). When called as:

```
      cbLoop2("ina", 3, 0.2);
```

it would generate (assuming the value of *length* is 20):

```
      for (i=0; i < 20; i++) {
          $ref(ina,i) = sin(i*0.6666666);
      }
```

In order to trigger the C++ expression processing via @-escapes in codeblocks which would otherwise have no arguments, add in a null argument list as in:

```
codeblock(cbLoop3,"") {
      for (i=0; i < @(int(length)); i++) {
          $ref(output,i) = sin(i*0.1);
      }
}
```

In the example above, the `@(int(length))` will be replaced with the value of the class member *length*. The above example would be called with an empty argument list as:

```
go {
      addCode(cbLoop3());
}
```

The complete parsing rules are:

```
@@         ==> @                (double "@" goes to single)
@ATSIGN    ==> @
@{         ==> {
@LBRACE    ==> {                (LBRACE is literal string)
@}         ==> }
@RBRACE    ==> }                (RBRACE is literal string)
@\         ==> \
@BACKSLASH ==> \                (BACKSLASH is literal string)
@id        ==> C++ token {id} (id is one or more alphanumerics)
@(expr)    ==> C++ expr {expr}(expr is arbitrary with balanced
```

```
            parens)
@(white_space) ==>                nothing
@anything_else is passed through unchanged (including the @)
```

In an extended codeblock, trailing backslashes "\" will omit the following newline in the generated code. This special meaning of trailing "\" may be prevented by using "@\" or "@BACKSLASH".

13.2.3 In-line codeblocks

Code blocks may be specified in the body of a method. Inside the definition of a method (such as `go()`), all contiguous blocks of lines with a leading `@` will be translated into an in-line codeblock (i.e., an `addCode()` statement). The `@` escape mechanism for C++ expressions works as described above for codeblocks with arguments. Within `@`-escaped expressions, in-line codeblocks may reference local method variables as well as member variables.

Leading white-space before a leading `@` will be ignored. Note that no override mechanism is provided to prevent the in-line codeblock interpretation. Note also that `@` has dual meanings: the first `@` on the line introduces in-line codeblock mode, while subsequent `@` characters on the same line escape into C++ expressions. For example:

```
go() {
        @CMAM_wait( &$ref(ackFlag), 1);
}
```

is equivalent to:

```
go() {
        addCode("CMAM_wait( &$ref(ackFlag), 1);\n");
}
```

A more complicated example:

```
go {
    @    $ref(output) = \
    int ni = input.numberPorts();
    for (int i = 1; i <= ni; i++) {
      @$ref(input#@i) @(i < ni ? " + " : ";\n") \
    }
}
```

If "`input.numberPorts()`" returns 3 when the above program is run, the generated code will be:

```
"    $ref(output) = $ref(input#1) + $ref(input#2) + $ref(input#3);\n"
```

Currently, only the pre-defined methods (`start`, `go`, `exectime` etc.) are processed this way; not user-defined methods.

13.2.4 Macros

In code generation stars, the inputs and outputs no longer hold values, but instead correspond to target resources where values will be stored (for example, memory locations/registers in assembler generation, or global variables in C-code generation). A star writer can also define states which can specify the need for global resources.

A code generation star, however, does not have knowledge of the available global resources or the global variables/tables which have already been defined in the generated code. For star writers, a set of macros to access the global resources is provided. The macros are expanded in a language or target specific manner after the target has allocated the resources properly. In this section, we discuss the macros defined in the `CGStar` class.

`$ref(name)`
: Returns a reference to a state or a port. If the argument, name, refers to a port, it is functionally equivalent to the `name%0` operator in the SDF simulation stars. If a star has a multi-porthole, say *input*, the first real porthole is *input#1*. To access the first porthole, we use `$ref(input#1)` or `$ref(input#internal_state)` where `internal_state` is the name of a state that has the current value, 1.

`$ref(name,offset)`
: Returns a reference to an array state or a port with an offset that is not negative. For a port, it is functionally equivalent to `name%offset` in SDF simulation stars.

`$val(state-name)`
: Returns the current value of the state. If the state is an array state, the macro will return a string of all the elements of the array spaced by the new line character. The advantage of not using `$ref` macro in place of `$val` is that no additional target resources need to be allocated.

`$size(name)`
: Returns the size of the state/port argument. The size of a non-array state is one; the size of a array state is the total number of elements in the array. The size of a port is the buffer size allocated to the port. The buffer size is usually larger than the number of tokens consumed or produced through that port.

`$starName()`
: Returns the instantiated name of the star (without galaxy or universe names)

`$fullName()`
: Returns the complete name of the star including the galaxies to which it belongs.

`$starSymbol(name)`
: Returns a unique label in the star instance scope. The instance scope is owned by a particular instance of that star in a graph. Furthermore, the scope is alive across all firings of that particular star. For example, two CG stars will have two distinct star instance scopes. As an example, we show some parts of ptlang

file of the CGCPrinter star.

```
initCode {
...
     StringList s;
     s << " FILE* $starSymbol(fp);";
     addDeclaration(s);
     addInclude("<stdio.h>");
     addCode(openfile);
...
}
codeblock (openfile) {
     if(!($starSymbol(fp)=fopen("$val(fileName)","w"))) {
          fprintf(stderr,"ERROR: cannot open output file
for Printer star.\n");
     exit(1);
     }
}
```

The file pointer fp for a star instance should be unique globally, and the $starSymbol macro guarantees the uniqueness. Within the same star instance, the macro returns the same label.

`$sharedSymbol(list,name)`

Returns the symbol for name in the list scope. This macro is provided so that various stars in the graph can share the same data structures such as sin/cos lookup tables and conversion table from linear to mu-law PCM encoder. These global data structures should be created and initialized once in the generated code. The macro sharedSymbol does not provide the method to generate the code, but does provide the method to create a label for the code. To generate the code only once, refer to “Code streams” on page 13-16. A example where a shared symbol is used is in CGCPCM star.

```
codeblock (sharedDeclarations)
{
      int $sharedSymbol(PCM,offset)[8];
      /* Convert from linear to mu-law */
      int $sharedSymbol(PCM,mulaw)(x)
      double x;
      {
            double m;
            m = (pow(256.0,fabs(x)) - 1.0) / 255.0;
            return 4080.0 * m;
      }
}
codeblock (sharedInit)
{
      /* Initialize PCM offset table. */
      {
      int i;
      double x = 0.0;
      double dx = 0.125;
      for(i = 0; i < 8; i++, x += dx)
      {
            $sharedSymbol(PCM,offset)[i] =
                              $sharedSymbol(PCM,mulaw)(x);
      }
}
initCode {
...
      if (addGlobal(sharedDeclarations, "$sharedSym-
bol(PCM,PCM)"))
      addCode(sharedInit);
}
```

The above code creates a conversion table and a conversion function from linear to mu-law PCM encoder. The conversion table is named `offset` and belongs to the `PCM` class. The conversion function is named `mulaw`, and belongs to the same PCM class. Other stars can access that table or function by saying `$sharedSymbol(PCM,offset)` or `$sharedSymbol(PCM,mulaw)`. The `initCode` method tries to put the `sharedDeclarations` codeblock into the global scope (by `addGlobal()` method in the CGC domain). That code block is given a unique label by `$sharedSymbol(PCM,PCM)`. If the codeblock has not been previously defined, `addGlobal` returns true, thus allowing `addCode(sharedInit)`. If there is more than one instance of the PCM star, only one instance will succeed in adding the code.

`$label(name), $codeblockSymbol(name)`

Returns a unique symbol in the codeblock scope. Both label and codeblockSymbol refer to the same macro expansion. The codeblock scope only lives as long as a codeblock is having code generated from it. Thus if a star uses `addCode()` more than once on a particular codeblock, all codeblock

instances will have unique symbols. A example of where this is used in the `CG56HostOut` star.

```
codeblock(cbSingleBlocking) {
$label(wait)
jclr #m_htde,x:m_hsr,$label(wait)
jclr #0,x:m_pbddr,$label(wait)
movep $ref(input),x:m_htx
}
codeblock(cbMultiBlocking) {
move #$addr(input),r0
.LOOP #$val(samplesOutput)
$label(wait)
jclr #m_htde,x:m_hsr,$label(wait)
jclr #0,x:m_pbddr,$label(wait)
movep x:(r0)+,x:m_htx
.ENDL
nop
}
```

The above two codeblocks use a label named *wait*. The `$label` macro will assign unique strings for each codeblock.

The base `CGStar` class provides the above 8 macros. In the derived classes, we can add more macros, or redefine the meaning of these macros. Refer to each domain document to see how these macros are actually expanded. There are three commonly used macros in the assembly code generation domains; these are:

`$addr(name)`

This returns the address of the allocated memory location for the given state or porthole name. The address does not include references to the memory bank the location is coming from; for instance, “x:2034” for location 2034 in the “x” memory bank for Motorola 56000 is output as 2034.

`$addr(name,<offset>)`

This macro returns the numeric address in memory of the named object, without (for the 56000) an “x:” or “y:” prefix. If the given quantity is allocated in a register (not yet supported) this function returns an error. It is also an error if the argument is undefined or is a state that is not assigned to memory (e.g. a parameter).

Note that this does NOT necessarily return the address of the beginning of a porthole buffer; it returns the “access point” to be used by this star invocation, and in cases where the star is fired multiple times, this will typically be different from execution to execution.

If the optional argument offset is specified, the macro returns an expression that references the location at the specified offset -- wrapping around to the beginning of the buffer if that is necessary. Note that this wrapping works independent of whether the buffer is circularly aligned or not.

`$ref(name,<offset>)`

This macro is much like $addr(name), only the full expression used to refer to this object is returned, e.g. “x:23” for a 56000 if “name” is in x memory. If “name” is assigned to a register, this expression will return the corresponding register. The error conditions are the same as for $addr

`$mem(name)`
: Returns the name of the memory bank in which the given state or porthole has its memory allocated.

To have “$” appear in the output code, put “$$” in the codeblock. For a domain where “$” is a frequently used character in the target language, it is possible to use a different character instead by redefining the virtual function `substChar` (defined in `CGStar`) to return a different character.

It is also possible to introduce processor-specific macros, by overriding the virtual function `processMacro` (rooted in `CGStar`) to process any macros it recognizes and defer substitution on the rest by calling its parent’s `processMacro` method.

13.2.5 Assembly PortHoles

Here are some methods of class `AsmPortHole` that might be useful in assembly code generation stars:

`bufSize()` Returns an integer, the size of the buffer associated with the porthole.

`baseAddr()` Returns the base address of the porthole buffer

`bufPos()` Returns the offset position in the buffer, which ranges from 0 to `bufSize()`-1.

`circAccessThisTime()`
: This method returns true (nonzero) if the data to be read or written on this execution “wrap around”, so that accessing them in a linear order will not work.

13.2.6 Attributes

Attributes are assertions about the object they are applied to. Both states and portholes can have attributes. Attributes that apply to states have the prefix “`A_`”. Attributes that apply to portholes have the prefix “`P_`”. The following attributes are common to all code generation domains:

`A_GLOBAL`
: If set, this state is declared global so that it is accessible everywhere. Currently, it is only supported in the CGC domain.

`A_LOCAL`
: This is the opposite of `A_GLOBAL`.

`A_SHARED`
: A state that is shared among all stars that know its name, type, size.

`A_PRIVATE`

Opposite of A_SHARED.

The default for stars is A_LOCAL|A_PRIVATE. Right now, only A_SHARED|A_LOCAL is supported in the assembly language domains. This combination means that all stars will share the particular state across a processor. For all stars to share it in a universe the bits A_SHARED|A_GLOBAL need to be set; this combination is not implemented yet - the default method will probably restrict all the stars that share this state to the same processor.

A_CONSTANT
: The state value is not changed by the star's execution.

A_NONCONSTANT
: The state value is changed by the star's execution.

A_SETTABLE
: The user may set the value of this state from a user interface.

A_NONSETTABLE
: The user may not set the value of this state from a user interface (e.g. edit-parameters doesn't show it).

Applying an attribute to an object implies that some bits are to be "turned on", and others are to be "turned off". The underlying attribute bits have names beginning with AB_ for states, and PB_ for portholes. The only two bits that exist in all states are AB_CONST and AB_SETTABLE. By default, they are on for states, which means that the default state works like a parameter (you can set it from the user interface, and the star's execution does not change it).

For assembly language domains, the following attributes are defined:

A_CIRC
: If set, the memory for this state is allocated as a circular buffer, whose address is aligned to the next power of two greater than or equal to its length.

A_CONSEC
: If set, allocate the memory for the *next* state in this star consecutively, starting immediately after the memory for this star.

A_MEMORY
: If set, memory is allocated for this state.

A_NOINIT
: If set, the state is not be automatically initialized. The default is that all states that occupy memory are initialized to their default values.

A_REVERSE
: If set, write out the values for this state in reverse order.

A_SYMMETRIC
: If set, and if the target has dual data memory banks (e.g. M56000, Analog Devices 2100, etc.), allocate a buffer for this object in both memories.

Given these attributes (technically, the above also have "bit" representations of the form AB_xxx; A_xxx just turns the bit AB_xxx on), the following attributes correspond to requests to turn some attributes off and to turn other attributes on. For example:

`A_ROM`
: Allocate memory for this state in memory, and the value will not change -- `A_MEMORY` and `A_CONSTANT` set.

`A_RAM`
: `A_MEMORY` set, `A_CONST` not set

For portholes in code generation stars, we have:

`P_CIRC`
: If set, then allocate the buffer for this porthole as a circular buffer, even if this is not required because of any other consideration.

`P_SHARED`
: Equivalent to `A_SHARED`, only for portholes.

`P_SYMMETRIC`
: Similar to `A_SYMMETRIC`, but for portholes.

`P_NOINIT`
: Do not initialize this porthole.

Attributes can be combined with the "`|`" operator. For example, to allocate memory for a state but make it non-settable by the user, I can say

```
AB_MEMORY|A_NONSETTABLE
```

13.2.7 Possibilities for effective buffering

In principle, blocks communicate with each other through porthole connections. In code generation domains, we allocate a buffer for each input-output connection by default. There are some stars, however, that do not modify data at all. A good, and also ubiquitous, example is a `Fork` star. When a `Fork` star has *N* outputs, the default behavior is to create *N* buffers for output connections and copy data from input buffer to *N* output buffers, which is a very expensive and silly approach. Therefore, we pay special attention to stars displaying this type of behavior. In the setup method of these stars, the `forkInit()` method is invoked to indicate that the star is a `Fork`-type star. For example, the `CGCFork` star is defined as

```
defstar {
name { Fork }
domain { CGC }
desc { Copy input to all outputs }
version { @(#)CGCFork.pl 1.6 11/11/92 }
author { E. A. Lee }
copyright { 1991-1994 The Regents of the University of Cali-
fornia }
location { CGC demo library }
explanation {
```

```
Each input is copied to every output. This is done by the way
the buffers are laid out; no code is required.
}
input {
      name {input}
      type {ANYTYPE}
}
outmulti {
      name {output}
      type {=input}
}
constructor {
      noInternalState();
}
start {
      forkInit(input,output);
}
exectime { return 0;}
}
```

Where possible, code generation domains take advantage of `Fork`-type stars by not allocating output buffers, but instead the stars reuse the input buffers. Unfortunately, in the current implementation, assembly language fork stars can not do their magic if the buffer size gets too large (specifically, if the size of the buffer that must be allocated is greater than the total number of tokens generated or read by some port during the entire execution of the schedule). Here, forks or delay stars that copy inputs to outputs must be used.

Another example of a `Fork`-Type star is the `Spread` star. The star receives *N* tokens and spreads them to more than one destination. Thus, each output buffer may share a subset of its input buffer. We call this relationship *embedding*: the outputs are embedded in the input. For example, in the `CGCSpread` star:

```
setup {
      MPHIter iter(output);
      CGCPortHole* p;
      int loc = 0;
      while ((p = (CGCPortHole*) iter++) != 0) {
            input.embed(*p, loc);
            loc += p->numXfer();
      }
}
```

Notice that the output is a multi-porthole. During setup, we express how each output is embedded in the input starting at location *loc*. At the buffer allocation stage, we do not allocate buffers for the outputs, but instead reuse the input buffer for all outputs. This feature, however, has not yet been implemented in the assembly language generation domains.

A `Collect` star embeds its inputs in its output buffer:

```
setup {
      MPHIter iter(input);
```

```
        CGCPortHole* p;
        int loc = 0;
        while ((p = (CGCPortHole*) iter++) != 0) {
              output.embed(*p, loc);
              loc += p->numXfer();
        }
    }
```

Other examples of embedded relationships are `UpSample` and `DownSample` stars. One restriction of embedding, however, is that the embedded buffer must be static. Automatic insertion of `Spread` and `Collect` stars in multi-processor targets (refer to the target section) guarantees static buffering. If there is no delay (i.e., no initial token) in the embedded buffer, static buffering is enforced by default. A buffer is called *static* when a star instance consumes or produces data in the same buffer location in any schedule period. Static buffering requires a size that divides the least common multiple of the number of tokens consumed and produced; if such a size exists that equals or exceeds the maximum number of data values that will ever be in the buffer, static allocation is performed.

13.3 Targets

A code generation `Domain` is specific to the language generated, such as C (CGC), Sproc assembly code (Sproc) [Mur93], Silage [Kal93], DSP56000 assembly code (CG56), and DSP96000 assembly code (CG96). Each code generation domain has a default target which defines routines generic to the target language. A derived `Target` that defines architecture specific routines can then be written. A given language, particularly a generic language such as C, may run on many target architectures. Code generation functions are cleanly divided between the default domain target and the architecture specific target.

All target architectures are derived from the base class `Target`. The special class `KnownTarget` is used to add targets to the known list of targets, much as `KnownBlock` is used to add stars (and other blocks) to the known block list and to assign names to them.

A `Target` object has methods for generating a schedule, compiling the code, and running the code (which may involve downloading code to target hardware and beginning its execution). There also may be child targets (for representing multiprocessor targets) together with methods for scheduling the communication between them. Targets also have parameters that are user specified.

13.3.1 Single-processor target

The base target for all code generation domains is the `CGTarget`, which represents a single processor by default. This target is called *default-CG* in the target list for the CG domain. As the generic code generation target, the `CGTarget` class defines many common functions for code generation targets. Methods defined here include virtual methods to generate, display, compile, and run the code. Derived targets are free to redefine these virtual methods if necessary.

Code streams

A code generation target manages code streams which are used to store star and target generated code. The `CGTarget` class has the two predefined code streams: `myCode` and `pro-`

cedures. The myCode stream is referred to as CODE and the procedures stream is called PROCEDURE; these names should be used when referring to these streams as in "CodeStream* code = getStream(CODE)". Derived targets are free to add more code streams using the CGTarget method addStream(*stream-name*). For example, the default CGC target defines fourteen additional code streams.

Other methods, such as addProcedure(code,*uniquename*) can be defined, to provide a more efficient or convenient interface to a specific code stream (in this case, procedures). With addProcedure it becomes clear why unique names are necessary. Recall that addProcedure is used to declarations outside of the main body of the code. For example, say we wanted to write a function in C to multiply two numbers. The codeblock to do this could read:

```
codeblock(sillyMultiply) {
/* A silly function */
double $sharedSymbol(silly,mult)(double a, double b)
{
     double m;
     m = a*b;
     return m;
}
}
```

Note that in this codeblock we used the sharedSymbol macro described in the code generation macros section. To add this code to the procedures stream, in the initCode method of the star, we can call either:

```
addProcedure(sillyMultiply,"mult");
```

or

```
addCode(sillyMultiply,"procedures","mult");
```

or

```
getStream("procedures")->put(sillyMultiply,"mult");
```

As with addCode, addProcedure returns a TRUE or FALSE indicating whether the code was inserted into the code stream. Taking this into account, we could have added the code line by line:

```
if (addProcedure("/* A silly function */\n","mult")) {
     addProcedure(
     "double $sharedSymbol(silly,mult)(double a, double
b)\n"
     );
     addProcedure("{\n");
     addProcedure("\tdouble m;\n");
     addProcedure("\tm = a*b;\n");
     addProcedure("\treturn m;\n");
     addProcedure("}\n");
}
```

13.3.2 Assembly code streams

Code is generated in the assembly language domains into four streams. The streams inherited from CGTarget are the CODE and PROCEDURES stream. The two new streams are:

`mainLoop` Code added to this stream comprises the main loop of the generated algorithm. All `addCode` calls from a star's `go` function automatically are concatenated to this stream unless another stream is supplied as an argument.

`trailer` Code added to this stream comprises the `wrapup` section of the generated algorithm. All `addCode` calls from a star's `wrapup` method automatically are concatenated to this stream unless another stream is supplied as an argument.

Code generation

Once the program graph is scheduled, the target generates the code in the virtual method `generateCode()`. (Note: code streams should be initialized before this method is called.) All the methods called by `generateCode` are virtual, thus allowing for target customization. The `generateCode` method then calls `allocateMemory()` which allocates the target resources. After resources are allocated, the `initCode` method of the stars are called by `codeGenInit()`. The next step is to form the main loop by calling the method `mainLoopCode()`. The number of iteration cycles are determined by the argument of the "run" directive which a user specifies in `pigi` or in `ptcl`. To complete the body of the main loop, `go()` methods of stars are called in the scheduled order. After forming the main loop, the `wrapup()` methods of stars are called.

Now, all of the code has been generated; however, the code can be in multiple target streams. The `frameCode()` method is then called to piece the code streams together and place the unified stream into the `myCode` stream. Finally, the code is written to a file by the method `writeCode()`. The default file name is "*`code.output`*", and that file will be located in the directory specified by a target parameter, *`destDirectory`*.

Finally, since all of the code has been generated for a target, we are ready to compile, load, and execute the code. Derived targets should redefine the virtual methods `compileCode()`, `loadCode()`, and `runCode()` to do these operations. At times it does not make sense to have separate `loadCode()` and `runCode()` methods, and in these cases, these operations should be collapsed into the `runCode()` method.

13.3.3 Multiprocessor targets

Targets representing multiple processors are derived from the `CGTarget` class. The base class for all multiple-processor targets is called `MultiTarget`, and resides in the `$(PTOLEMY)/src/domains/cg/kernel` directory. `CGMultiTarget` is derived from `MultiTarget`. `CGMultiTarget` class is the base class for all multiple-processor targets. It is called *FullyConnected* in the CG domain target list.

The design of Ptolemy is also intended to support heterogeneous multi-processor targets. In the future, the base class of all "abstract" heterogeneous multiprocessor targets will be implemented from the `MultiTarget` class. For such targets, certain actors must be assigned to certain targets, and the cost of a given actor is in general a function of which child target it is assigned to. We have developed parallel schedulers that address this problem [Sih91].

We have implemented, or are in the process of implementing, both "abstract" and "concrete" multi-processor targets. For example, we have classes named `CGMultiTarget`

and CGSharedBus that represent sets of homogenous single-processor targets of arbitrary type, connected in either a fully connected or shared-bus topology, with parametrized communication costs. These targets, however, use only the CG domain stars and hence do not actually generate code (recall that CG domain stars are "comment generators"). Some other actual implementations of multiprocessor systems include the CM-5 (CGCCm5Target in the CGC domain), the Sproc multiprocessor DSP [Mur93], and the ordered transaction architecture [Sri93]. Refer to the CG56 domain documentation for CG56MultiSim target, or the CGC domain documentation for CGCMultiTarget class as examples of "concrete" multi-processor targets. In this section, we concentrate on the "abstract" multiprocessor target classes that are in the $(PTOLEMY)/src/domains/cg/targets directory.

CGMultiTarget is the base target class for all homogeneous targets. By default, it models a fully-connected multiprocessor architecture; when a processor wants to communicate with another processor, it can do immediately. The scheduleComm() method returns the time when the required communication is scheduled. In the CGMultiTarget class, it returns the same time as when the communication is required. On the other hand, CGSharedBus, which is derived from the CGMultiTarget class, is the base target class for all multiprocessor targets having a shared-bus topology. In the CGSharedBus class, the scheduleComm() method schedules the required communication on the shared-bus member object of that class, and returns the scheduled time. The communication cost (in time) is modeled by the commTime() method. Given the information on which processors are involved in this communication and how many tokens are transmitted, it returns the expected communication time once started. By default (or in fully-connected topology), it only depends on the number of tokens.

A CGMultiTarget has a sequence of child target objects to represent each of the individual processors. The number of processors are determined by an IntState, nprocs, and the type of the child target is specified by a StringState, childType. Refer to the *User's Manual* for details on how to specify the various target parameters. In the setup stage, the child targets are created and added to the child target list as members of the multiprocessor target. Classes derived from MultiTarget represent the topology of the multi-processor network (communication costs between processors, schedules for use of communication facilities, etc.), and single-processor child targets can represent arbitrary types of processors. The resource allocation problem is divided between the parent target, representing the shared resources, and the child targets, representing the resources that are local to each processor.

The main role of a multiprocessor target is to set up one of the chosen parallel schedulers, and to coordinate the child targets. The CGMultiTarget class has a set of parameters to select parallel scheduling options. See the schedulers section for a detailed discussion on parallel schedulers. The selected parallel scheduler schedules the program graph onto the child targets and the scheduling results are displayed on a Gantt chart. The parent multiprocessor target collects the code from each of the child targets after the child targets have generated code based on the scheduling results. By default, it merges all of the child-processor code into a single file. If separate files are required, then one approach is to create separate files with names derived from the child target names and write the code to these files in the frameCode() method of the multi-target.

Interprocessor communication (IPC) stars are created by the multiprocessor target by the methods createSend() and createReceive(). These stars are spliced in to the sub-

galaxies that are created and handed down to the child targets. Typically, these methods just create the appropriate IPC star and return a pointer to the object created. Each send/receive pair is matched in the `pairSendReceive()` method. Typically, this might involve setting pointers in the send/receive pair to point to each other.

There is no preprocessor for targets like `ptlang` for stars. Designing a customized multiprocessor target, therefore, is a bit complicated compared to designing a customized star. If the interconnection topology is neither fully-connected nor shared-bus, in particular, the communication scheduling should be designed in the target, which makes a target design more complicated. So the best way to design a target is to look at an already-implemented target such as `CGCMultiTarget` class in the CGC domain.

13.4 Schedulers

Given a Universe of functional blocks to be scheduled and a `Target` describing the topology and characteristics of the single- or multiple-processor system for which code is to be generated, it is the responsibility of the `Scheduler` object to perform some or all of the following functions:

- Determine which processor a given invocation of a given `Block` is executed on (for multiprocessor systems).
- Determine the order in which actors are to be executed on a processor.
- Arrange the execution of actors into standard control structures, like nested loops.

In this section, we explain different scheduling options and their effect on the generated code.

13.4.1 Single-processor schedulers

For targets consisting of a single processor, we provide three different scheduling techniques. The user can select the most appropriate scheduler for a given application by setting the `loopingLevel` target parameter.

In the first approach (`loopingLevel` = DEF), which is the default SDF scheduler, we conceptually construct the acyclic precedence graph (APG) corresponding to the system, and generate a schedule that is consistent with that precedence graph. Note that the precedence graph is not physically constructed. There are many possible schedules for all but the most trivial graphs; the schedule chosen takes resource costs, such as the necessity of flushing registers and the amount of buffering required, into account. The target then generates code by executing the actors in the sequence defined by this schedule. This is a quick and efficient approach when the SDF graph does not have large sample-rate changes. If there are large sample-rate changes, the size of the generated code can be huge because the codeblock for an actor might occur many times (if the number of repetitions for the actor is greater than one); in this case, it is better to use some form of *loop* scheduling.

We call the second approach *Joe's* scheduler. In this approach (`loopingLevel` = CLUST), actors that have the same sample rate are merged (wherever this will not cause deadlock) and loops are introduced to match the sample rates. The result is a hierarchical clustering; within each cluster, the techniques described above can be used to generate a schedule. The code then contains nested loop constructs together with sequences of code from the actors.

Since the second approach is a heuristic solution, there are cases where some looping possibilities go undetected. By setting the `loopingLevel` to SJS, we can choose the third approach, called *SJS* (Shuvra-Joe-Soonhoi) scheduling after the inventor's first names [Bha94]. After performing Joe's scheduling at the front end, it attacks the remaining graph with an algorithm that is guaranteed to find the maximum amount of looping available in the graph.

A fourth approach, obtained by setting `loopingLevel` to ACYLOOP, we choose a scheduler that generates single appearance schedules optimized for buffer memory usage. This scheduler was developed by Praveen Murthy and Shuvra 'Bhattacharyya [Mur96] [Bha96]. This scheduler only tackles acyclic SDF graphs, and if it finds that the universe is not acyclic, it automatically resets the *loopingLevel* target parameter to SJS. Basically, for a given SDF graph, there could be many different single appearance schedules. These are all optimally compact in terms of schedule length (or program memory in inline code generation). However, they will, in general, require differing amounts of buffering memory; the difference in the buffer memory requirement of an arbitrary single appearance schedule versus a single appearance schedule optimized for buffer memory usage can be dramatic. In code generation, it is essential that the memory consumption be minimal, especially when generating code for embedded DSP processors since these chips have very limited amounts of on-chip memory. Note that acyclic SDF graphs always have single appearance schedules; hence, this scheduler will always give single appearance schedules. If the `file` target parameter is set, then a summary of internal scheduling steps will be written to that file. Essentially, two different heuristics are used by the ACYLOOP scheduler, called APGAN and RPMC, and the better one of the two is selected. The generated file will contain the schedule generated by each algorithm, the resulting buffer memory requirement, and a lower bound on the buffer memory requirement (called BMLB) over all possible single appearance schedules.

If the second, third, or fourth approach is taken, the code size is drastically reduced when there are large sample rate changes in the application. On the other hand, we sacrifice some efficient buffer management schemes. For example, suppose that star A produces 5 samples to star B which consumes 1 sample at a time. If we take the first approach, we schedule this graph as ABBBBB and assign a buffer of size 5 between star A and B. Since each invocation of star B knows the exact location in the allocated buffer from which to read its sample, each B invocation can read the sample directly from the buffer. If we choose the second, third, or fourth approach, the scheduling result will be A5(B). Since the body of star B is included inside a loop of factor 5, we have to use indirect addressing for star B to read a sample from the buffer. Therefore, we need an additional buffer pointer for star B (memory overhead), and one more level of memory access (runtime overhead) for indirect addressing.

13.4.2 Multiprocessor schedulers

A key idea in Ptolemy is that there is no single scheduler that is expected to handle all situations. Users can write schedulers and can use them in conjunction with schedulers we have written. As with the rest of Ptolemy, schedulers are written following object-oriented design principles. Thus a user would never have to write a scheduler from ground up, and in fact the user is free to derive the new scheduler from even our most advanced schedulers. We have designed a suite of specialized schedulers that can be mixed and matched for specific applications.

The first step in multiprocessor scheduling, or parallel scheduling, is to translate a given SDF graph to an acyclic precedence expanded graph (APEG). The APEG describes the dependency between invocations of blocks in the SDF graph during execution of one iteration. Refer to the SDF domain documentation for the meaning of one iteration. Hence, a block in a multirate SDF graph may correspond to several APEG nodes. Parallel schedulers schedule the APEG nodes onto processors.

We have implemented three scheduling techniques that map SDF graphs onto multiple-processors with various interconnection topologies: Hu's level-based list scheduling, Sih's dynamic level scheduling [Sih91], and Sih's declustering scheduling [Sih91]. The target architecture is described by its `Target` object, derived from `CGMultiTarget`. The Target class provides the scheduler with the necessary information on interprocessor communication to enable both scheduling and code synthesis.

The `CGMultiTarget` has a parameter, *schedName*, that allows the user to select the type of schedule. Currently, there are five different scheduling options:

`DL` — If *schedName* is set to `DL`, we select the Sih's dynamic level scheduler that accounts for IPC overhead during scheduling.

`HU` — Hu's level scheduler is selected, which ignores the IPC overhead.

`DC` — The Sih's declustering scheduler can be selected by setting `DC`. The declustering algorithm is advantageous only when the list scheduling algorithm shows poor performance, judged from the scheduling result because it is more expensive than the `DL` or `HU` scheduler.

`HIER(DL)` or `HIER(HU)` or `HIER(DC)` — If we want to use Pino's hierarchical scheduler, we have to set *schedName* to `HIER(DL` or `HU` or `DC)`. The default top-level scheduling option is the `DL` scheduler. To use other scheduler, `DC` or `HU` should be specified within the parenthesis.

`CGDDF` — If the *schedName* is set to `CGDDF`, the Ha's dynamic construct scheduler is selected. To use this scheduler, Ptolemy should be recompiled with special flags, or use `mkcgddf` executable.

Whichever scheduler is used, we schedule communication nodes in the generated code. For example, if we use the Hu's level-based list scheduler, we ignore communication overhead when assigning stars to processors. Hence, the code is likely to contain more communication stars than with the other schedulers that do not ignore IPC overhead.

There are other target parameters that direct the scheduling procedure. If the parameter `manualAssignment` is set to `YES`, then the default parallel scheduler does not perform star assignment. Instead, it checks the processor assignment of all stars (set using the `procId` state of CG and derived stars). By default, the `procId` state is set to -1, which is an illegal assignment since the child target is numbered from 0. If there is any star, except the `Fork` star, that has an illegal `procId` state, an error is generated saying that manual scheduling has failed. Otherwise, we invoke a list scheduler that determines the order of execution of blocks on each processor based on the manual assignment. We do not support the case where a block might

require more than one processor. The `manualAssignment` option automatically sets the `oneStarOneProc` state to be discussed next.

If there are sample rate changes, a star in the program graph may be invoked multiple times in each iteration. These invocations may be assigned to multiple processors by default. We can prevent this by setting the `oneStarOneProc` state to `YES`. Then, all invocations of a star are assigned to the same processor regardless of whether they are parallelizable or not. The advantage of doing this is the simplicity in code generation since we do not need to splice in `Spread/Collect` stars, which will be discussed later. Also, it provides us another possible scheduling option: `adjustSchedule`; this is described below. The main disadvantage of setting `oneStarOneProc` to `YES` is the performance loss of not exploiting parallelism. It is most severe if Sih's declustering algorithm is used. Therefore, Sih's declustering algorithm is not recommended with this option.

In this paragraph, we describe a future scheduling option which this release does not support yet. Once automatic scheduling (with `oneStarOneProc` option set) is performed, the processor assignment of each star is determined. After examining the assignment, the user may want to override the scheduling decision manually. It can be done by setting the `adjustSchedule` parameter. If that parameter is set, after the automatic scheduling is performed, the `procId` state of each star is automatically updated with the assigned processor. The programmer can override the scheduling decision by setting that state. The `adjustSchedule` cannot be `YES` before any scheduling decision is made previously. Again, this option is not supported in this release.

Different scheduling options result in different assignments of APEG nodes. Regardless of which scheduling options are chosen, the final stage of the scheduling is to decide the execution order of stars including send/receive stars. This is done by a simple list scheduling algorithm in each child target. The final scheduling results are displayed on a Gantt chart. The multiple-processor scheduler produces a list of single processor schedules, giving them to the child targets. The schedules include send/receive stars for interprocessor communication. The child targets take their schedules and generate code.

To produce code for child targets, we create a sub-galaxy for each child target, which consists of the stars scheduled on that target and some extra stars to be discussed below if necessary. A child target follows the same step to generate code as a single processor target except that the schedule is not computed again since the scheduling result is inherited from the parent target.

Send/Receive stars

After the assignment of APEG nodes is finished, the interprocessor communication requirements between blocks are determined in sub-galaxies. Suppose star A is connected to star B, and there is no sample rate change. By assigning star A and star B to different processors (1 and 2 respectively), the parallel scheduler introduces interprocessor communication. Then, processor 1 should generate code for star A and a "send" star, while processor 2 should generate code for a "receive" star and star B. These "send" and "receive" stars are inserted automatically by the Ptolemy kernel when determining the execution order of blocks in each child target and creating the sub-galaxies. The actual creation of send/receive stars is done by the parallel scheduler by invoking methods (`createSend()` and `createReceive()`, as mentioned earlier) in the parent multi-target.

Once the generated code is loaded, processors run autonomously. The synchronization protocol between processors is hardwired into the “send” and “receive” stars. One common approach in shared-memory architectures is the use of semaphores. Thus a typical synchronization protocol is to have the send star set a flag when it completes the data transfer, and have the receive star read the data and reset the semaphore. The receive star will not read the data if the semaphore has not been set and similarly, the send star will not write data if the semaphore has not been reset. In a message passing architecture, the send star may form a message header to specify the source and destination processors. In this case, the receive star would decode the message by examining the message header.

For properly supporting arbitrary data types, the send star should have an `ANYTYPE` input; the receive star should have an `ANYTYPE` output. The resolved type for each of these ports can be obtained using the `Porthole::resolvedType` method. For a preliminary version of the communication stars, you can use a fixed datatype such as `FLOAT` or `INT`.

The send/receive stars that are declared to support `ANYTYPE` but fail to support a particular datatype, should display an appropriate error message using the `Error::abortRun` method. Finally, each of these stars must call `PortHole::numXfer` to determine the size of the block of data that needs to be transferred upon each invocation.

Spread/Collect stars

Consider a multi-rate example in which star A produces two tokens and star B consumes one token each time. Suppose that the first invocation of star B is assigned to the same processor as the star A (processor 1), but the second invocation is assigned to processor 2. After star A fires in processor 1, the first token produced should be routed to star B assigned to the same processor while the second token produced should be shipped to processor 2; interprocessor communication is required! Since star A has one output port and that port should be connected to two different destinations (one is to star B, the other is to a “send” star), we insert a “spread” star after star A. As a result, the sub-galaxy created for processor 1 contains 4 blocks: star A is connected to a “spread” star, which in turn has two outputs connected to star B and a “send” star. The role of a “spread” star is to spread tokens from a single output porthole to multiple destinations.

On the other hand, we may need to “collect” tokens from multiple sources to a single input porthole. Suppose we reverse the connections in the above example: star B produces one token and star A consumes two tokens. We have to insert a “collect” star at the input porthole of star A to collect tokens from star B and a “receive” star that receives a token from processor 2.

The “spread” and “collect” stars are automatically inserted by the scheduler, and are invisible to the user. Moreover, these stars can not be scheduled. They are added to sub-galaxies only for the allocation of memory and other resources before generating code. The “spread” and “collect” stars themselves do not require extra memory since in most cases we can overlay memory buffers. For example, in the first example, a buffer of size 2 is assigned to the output of star A. Star B obtains the information it needs to fetch a token from the first location of the buffer via the “spread” star, while the “send” star knows that it will fetch a token from the second location. Thus, the buffers for the outputs of the “spread” star are overlaid with the output buffer of star A.

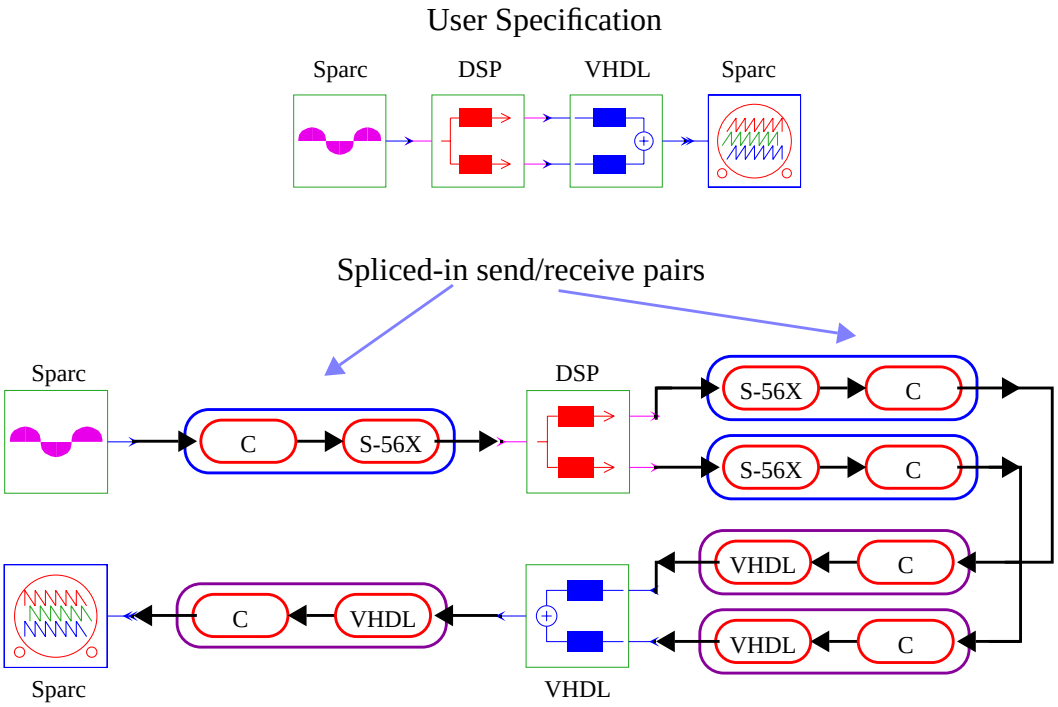

FIGURE 13-1: An interface constructed between three code generation domains. The interface constructed by the framework is made up of communication pairs, each pair encircled by an ellipse. The first (sine) and last (xgraph) stars are to be run on the host workstation (CGC). The second block (analysis filter bank, a galaxy made up of two polyphase FIR actors) is to be run on a DSP card (CG56). The third block (synthesis filter bank, a galaxy made up of two polyphase FIR actors) is to be run using a VHDL simulator.

In case there are delays or past tokens are used on the connection between two blocks that should be connected through “spread” or “collect” stars, we need to copy data explicitly. Thus, we will need extra memory for these stars. In this case, the user will see the existence of “spread/collect” stars in the generated code.

`Spread`/`Collect` stars have only been implemented in the CGC domain so far.

13.5 Interface Issues

In Ptolemy 0.6 and later, we have developed a framework for interfacing code generation targets with other targets (simulation or code generation). In this section we will detail how to support this new framework for a code generation target. To learn how to develop applications within Ptolemy that use multiple targets that support this new framework, refer to the *Interface Issues* section in the *User’s Manual - CG Domain* chapter.

As with `Wormholes`, we have developed a way to interface N targets without requiring N^2 specialized interfaces. We do this by generating a customized interface (analogous to the universal `EventHorizon` in wormholes) that is automatically built by using communication stars supplied by each code generation target. This interface is generated in C (using the CGC domain) and runs on the Ptolemy host workstation.

To support this infrastructure, a target writer needs to define two pairs of communica-

tion stars and add target methods which return each of these pairs. The framework will then build the interface by splicing in these stars as is shown in figure 13-1. These same actors are used when constructing an interface to a Ptolemy simulation target as shown in figure 13-2.

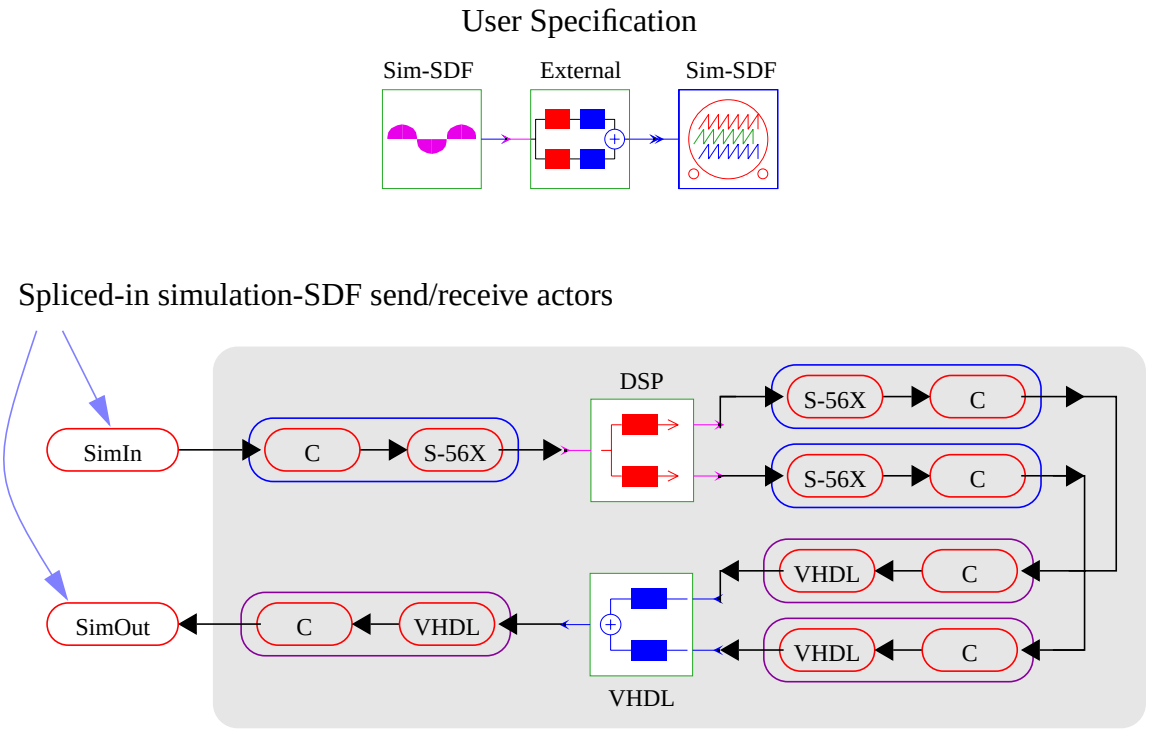

FIGURE 13-2: General Ptolemy simulation interface. The analysis and synthesis filter bank blocks are identical to those described in figure 13-1. The SimIn and SimOut stars are built into Ptolemy and defined in:
$PTOLEMY/src/domains/cgc/targets/main/CGCSDF{Send,Receive}.pl

These communication stars, described in section 13.4.2, are a specialized form of send/receive stars. In addition to the previous assumptions in section 13.4.2, send/receive for this infrastructure must also define C code to control the target for operations such as downloading, initializing and (if applicable) terminating the generated executable.

One pair of communication stars must communicate from the target to the CGC code that will run on the Ptolemy host workstation. The other pair must communicate in the opposite direction. The CGC send/receive stars are typically defined from a common base communication star specific for each target. This common base defines the C code to control a target that was discussed in the previous paragraphs. Examples of send/receive stars that support this infrastructure can be found in:

For the S56XTarget (Ariel S-56X DSP card):

```
$PTOLEMY/src/domains/cg56/targets/CGCXBase.pl
$PTOLEMY/src/domains/cg56/targets/CGCXSend.pl
$PTOLEMY/src/domains/cg56/targets/CGCXReceive.pl
$PTOLEMY/src/domains/cg56/targets/CG56XCSend.pl
$PTOLEMY/src/domains/cg56/targets/CG56XCReceive.pl
```

For the SimVSSTarget (Synopsis VSS Simulator):

```
$PTOLEMY/src/domains/vhdl/targets/CGCVSynchComm.pl
```

```
$PTOLEMY/src/domains/vhdl/targets/CGCVSend.pl
$PTOLEMY/src/domains/vhdl/targets/CGCVReceive.pl
$PTOLEMY/src/domains/vhdl/targets/VHDLCSend.pl
$PTOLEMY/src/domains/vhdl/targets/VHDLCReceive.pl
```

After defining both pairs of communication stars, methods to instantiate these stars must be defined in the target:

```
CommPair fromCGC(PortHole&);
CommPair toCGC(PortHole&);
```

A `CommPair` is a communication pair, where one of the communication stars in a CGC star. The `S56XTarget::fromCGC` method, illustrates the typical code needed for these methods:

```
CommPair S56XTarget::fromCGC(PortHole&) {
      CommPair pair(new CGCXSend,new CG56XCReceive);
      configureCommPair(pair);
      return pair;
}
```

The `configureCommPair` function is defined in the `S56XTarget.cc` file and configures the S56XTarget communication stars.

Chapter 14. CGC Domain

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14.1 Introduction

The CGC domain generates code for the `C` programming language. “Code Generation” on page 13-1 describes the features common to all code generation domains. The basic principles of writing code generation stars are explained in “Writing Code Generation Stars” on page 13-2.You will find explanations for codeblocks, macros, and attributes there. This chapter explains features specific to the CGC domain. Refer to the CGC domain chapter in the user’s manual for an introduction to this domain.

14.2 Code Generation Methods

The `addCode` method is context sensitive so that it will ‘do the right thing’ when invoked from within the `initCode`, `go`, and `wrapup` methods of `CGCStar`. Refer to “Writing Code Generation Stars” on page 13-2 for documentation on `addCode`, including context sensitive actions and conditional code generation. There are several additional code-generation methods defined in the CGC domain. The `addInclude` method is used to generate `#include` *file* directives. The `addDeclaration` method is used to declare local variables within the main function. The `addGlobal` method is used to declare global variables outside the main function. As with `addCode`, these methods return `TRUE` if code was generated for the appropriate stream and `FALSE` otherwise. These methods are member functions of the `CGCStar` class.

`int addInclude (const char* file)`
: Generate the directive `#include` *`file`* in the `include` stream. The string *file* must include quotation marks (`"`*`file`*`"`) or angle brackets (`<`*`file`*`>`) around the name of the file to be included. Only one `#include` *`file`* directive will be generated for the file, even if `addInclude` is invoked multiple times with the same argument. Return `TRUE` if a new directive was generated.

`int addDeclaration (const char* text, const char* name = NULL)`
: Add text to the `mainDecls` stream. Use *`name`* as the identifying key for the code fragment if it is provided, otherwise use

text itself as the key. Code will be added to the stream only the first time that a particular key is used.

`int addGlobal (const char* text, const char* name = NULL)`
Add text to the `globalDecls` stream. Use *name* as the identifying key for the code fragment if it is provided, otherwise use *text* itself as the key. Code will be added to the stream only the first time that a particular key is used.

`int addCompileOption (const char* text)`
Add options to be used when compiling a C program. The options are collected in the `compileOptionsStream` stream.

`int addLinkOption (const char* text)`
Add options to be used when linking a C program. The options are collected in the `linkOptionsStream` stream.

The following streams, which are used by the code generation methods just described, are defined as members of the `CGCTarget` class in addition to the streams defined by the `CGTarget` class.

`CodeStream include`
Include directives are added to this stream by the `addInclude` method of `CGCStar`.

`CodeStream mainDecls`
Local declarations for variables are added to this stream by the `addDeclaration` method of `CGCStar`.

`CodeStream globalDecls`
Global declarations for variables and functions are added to this stream by the `addGlobal` method of `CGCStar`.

`CodeStream mainInit`
Initialization code is added to this stream when the `addCode` method is invoked from within the `initCode` method.

`CodeStream mainClose`
Code generated when the `addCode` method is invoked from within the `wrapup` method of stars is placed in this stream.

`CodeStream compileOptionsStream`
Options to be passed to the C compiler which have been added using the `CGCStar::addCompileOption` method.

`CodeStream linkOptionsStream`
Options to be passed to the linker which have been added using the `CGCStar::addLinkOption` method.

14.3 Buffer Embedding

Although many of the methods related to buffer embedding are actually implemented in the CG domain, only the CGC domain makes use of them at this time. The following func-

tion is defined as a method of the `CGPortHole` class.

`void embed (CGPortHole` *`port`*`, int` *`location`* `= -1)`

Embed the buffer of *`port`* in the buffer of this porthole with offset *`location`*. The default *`location`* of -1 indicates that the offset is not yet determined.

For example, the following statements appear in the setup method of the `Switch` block. This causes the buffers of `trueOutput` and `falseOutput` to be embedded within the buffer of input.

```
input.embed(trueOutput,0);
input.embed(falseOutput,0);
```

14.4 Command-line Settable States

In the Ptolemy releases before Ptolemy0.6 the C programs generated by Ptolemy in the CGC domain did not take any command-line arguments. The state values of the various stars were set during compilation and thus hard-coded into the program. In order to change a state variable, the code had to be recompiled again (i.e. the universe had to be re-run within Ptolemy). This was time consuming, and it also placed unnecessary load on the machine. In Ptolemy0.6 and later, the CGC domain can generate C code that allow users to set the state values from the command-line, which allows runs with different parameters to be executed and compared quickly and easily.

Implementation

14.4.1 C code generated to support command line arguments

A sample of the additional code generated to support command-line arguments is shown below:

```
.
.
struct {
 double FOO;
 double BAR;
} arg_store = {1.0, 0.01,};

void set_arg_val(char *arg[]) {
 int i;
 for (i = 1; arg[i]; i++) {
 if ((!strcmp(arg[i], "-help")) \
      ||(!strcmp(arg[i], "-HELP")) \
      ||(!strcmp(arg[i], "-h"))) {
      printf("Settable states are :\n
             FOO\tdefault : 1.0\n
             BAR\tdefault : 0.01\n");
      exit(0);
 }
 if (!strcmp(arg[i], "-FOO")) {
      if (arg[i + 1])
       arg_store.FOO = atof(arg[i + 1]);
```

```
                continue;
        }
        if (!strcmp(arg[i], "-BAR")) {
             if (arg[i + 1])
              arg_store.BAR = atof(arg[i + 1]);
              continue;
        }
        }
}

/* main function */
      main(int argc, char *argv[]) {
      .
      .
       double value_11;
       double value_12;
      .
      .     // End of Declaration
       set_arg_val(argv);
      .     // Begin of Initialization
      .
       value_12 = arg_store.BAR;
       value_11 = arg_store.FOO;
      .     // Code
      .
      }
```

The default values (set by the "edit-parameters" command) are stored in the struct `arg_store`. The function `set_arg_val(argv)` scans the list of command-line arguments for `FOO` and `BAR` and sets the corresponding member in `arg_store`. It also builds up the help message (consist of the settable state names and their default values) to be printed when the program receives a '`-h`', '`-help`' or '`-HELP`' option. The state values are initialized to the corresponding `arg_store` members during the variable initialization stage. By doing this, a state will get its default value if it is not set on the command-line.

14.4.2 Changes in pigiRpc to support command line arguments

The pragma mechanism in the `Target` base class is used to specify the state that is to be made settable via command-line arguments as well as to store the name to be used on the command-line. In `CGCtarget`, these are stored as a character string in a `TextTable*` mappings (a pointer to a `HashTable` in which the data value and index are character strings) via the overloaded `pragma()` member functions.

A function, `isCmdArg(const State* state)`, is used to check whether '`state`' is to be set by a command-line argument. It calls `CGCTarget::pragma()` and scans through the `StringList` returned for the state's name. If found, the mapped name is return. Otherwise a null string is return.

Four new protected `CodeStream` are added to `CGCTarget` to store the additional codes:

`cmdargStruct` stores the struct members.

`cmdargStruct` stores the default values.

`setargFunc` stores the code segment in `set_arg_val()`.

`setargFuncHelp` stores the built-up help message.

Four new public member functions and four private ones are also added to `CGCStar` to generate the codes:

`cmdargStates()` calls `cmdargState()` to generate the members of `struct arg_store` using the mapped name returned by `isCmdArg()`.

`cmdargStatesInits()` calls `cmdargStatesInit()` to generate the default values of the settable states.

`setargStates()` calls `setargState()` to generate the code segment to match the mapped name to the command-line options.

`setargStatesHelps()` calls `setargStatesHelp()` to build up the help message.

These are called in the `CGCTarget::declareStar(CGCStar* star)` function after the global and main declarations have been generated. `CGCStar::initCodeState(const State* state)` is modified to generate the required initialization code if state is to be settable from the command-line.

In order for a `$val` state to be settable from the command-line, it has to be changed to a `reference state`. The `expandVal()` member function is overloaded in `CGCStar` to check if the "`name`" state is to be made settable from the command-line. If so, it is added to the list of referenced state so that it will be declared and initialized.

14.4.3 Limitations of command line arguments.

Currently, this implementation works only for scalar states with float or integer values. Extension to other types of state should be straight forward by simply adding the appropriate struct member declaration code in `CGCStar::cmdargState(const State* state)`. The `cmdargStatesInit()`, `setargState()`, `setargStatesHelp()` and `initCodeString()` member functions need to be modified accordingly to generate codes for the initialization, setting function, help message and assignment respectively of the new state variable.

Also, there is no provision to check for duplicate command-line names. If there are duplicates, Ptolemy will simply generate multiple `struct` members with the same name, and error will result in the generated code. To get around this, a new Tk interface could be written to specify and set the settable states and checking can be done at that level. Alternatively, it might be a better idea to use the `put()` method in `CodeStream` to add the `struct` member with its unique handle to the appropriate `CodeStream`. That way, there will not be duplicate `struct` members and state-variables could still reference the same member, so that two or more states could be set to the same value from a single argument on the command-line.

Another limitation is that the command-line capability only works for states of blocks at the top level. It will not work for states of `Galaxies` and `Universes`, and states that refer-

enced other settable states. This could probably be solved by modifying the pragma mechanism to ensure that `pragma`s at the top level propagate all the way down to the contained blocks. By doing this, states will inherit `pragma`s from their parent `galaxies` so that these can be picked up by the `isCmdArg()` function, and the appropriate codes can be generated.

Certain states will affect the overall scheduling of the whole system, e.g. the *factor* of `upsampling` and `downsampling` stars, and changing these would mean that new code needs to be generated since the scheduling is hard-coded into the generated code. Thus these should not be allowed to take values from the command-line. A new attribute can be introduced to identify those states that should not be settable from the command-line. Warnings can then be generated if users attempt to specify these for command-line setting.

14.5 CGC Compile-time Speed

There are several areas that can affect the amount of time that it takes a CGC universe to compile, we discuss them below.

- Large sample rate changes and large delays can result in Ptolemy taking a very long time to generate C code. A symptom of this sort of problem is that the `pigiRpc` process will consume all the available swap and eventually crash. If you feel you need really large delays, James Lundblad suggests writing your own code in your stars that provides the same functionality as delays, but uses `malloc()` in the `initCode` section instead of the array that is created by the CGC Delay icon.
- C compiler optimizers do not work well with functions that have thousands of lines. The `main()` function of a CGC simulation may be too large for the peephole optimizer, causing the optimizer to take a long time to compile the file. Under `gcc`, you can pass the `-O0` option to turn off the optimizer.

14.6 BDF Stars

Because the class `CGCPortHole` is not derived from `BDFPortHole`, the `setBDFParams` method described in “BDF Domain” on page 8-1 is not available for code generation stars. Use the `setRelation` method of `DynDFPortHole` instead.

`void setRelation (DFRelation` *`relation`*`, DynDFPortHole*` *`assoc`*`)`

Specify the *`relation`* of this port with the associated porthole *`assoc`*. There are five possible values for relation:

`DF_NONE`	no relationship.
`DF_TRUE`	produces/consumes data only when *`assoc`* has a `TRUE` particle.
`DF_FALSE`	produces/consumes data only when *`assoc`* has a `FALSE` particle.
`DF_SAME`	signal is logically the same as *`assoc`*.
`DF_COMPLEMENT`	signal is the logical complement of *`assoc`*.

For example, the following statements describe the relationships among the portholes of the `Switch` block.

```
trueOutput.setRelation(DF TRUE, control);
```

```
falseOutput.setRelation(DF FALSE, control);
```

14.7 Tcl/Tk Stars

The `CGCTclTkTarget` class defines the `tkSetup` stream for Tcl/Tk stars.There is no special code generation function for this stream, so its name must be used with `addCode`. This is usually done from within the `initCode` method.

```
addCode(codeblock, "tkSetup");
```

The following functions, which are defined in the file `tkMain.c`, can be used within codeblocks of Tcl/Tk stars in the CGC domain.

`void errorReport (char* message)`
: This functions creates a pop-up window containing *message*.

`void makeEntry (char* window, char* name, char* desc, char* initValue, Tcl CmdProc* callback)`
: This function creates an entry box in a *window*. The *name* of the entry box must be unique (e.g. derived from the star name). The description of the entry box is desc. The initial value in the entry box is *initValue*.

  A *callback* function is called whenever the user enters a `RET` in the box. The argument to the *callback* function will be the value that the user has put in the entry box. The return value of the *callback* function should be `TCL_OK`.

`void makeButton (char* window, char* name, char* desc, Tcl CmdProc* callback)`
: This function creates a push button in a *window*. The *name of* the push button must be unique (e.g. derived from the star name). The description of the push button is *desc*.

  A *callback* function is called whenever the user pushes the button. The return value of the *callback* function should be `TCL_OK`.

`void makeScale (char* window, char* name, char* desc, int position, Tcl CmdProc* callback)`
: This function creates a scale (with slider) in a *window*. The name of the scale must be unique (e.g., derived from the star name). The description of the push button is desc. The initial position of the slider must be between `0` and `100`.

  A *callback* function is called whenever the user moves the slider in the scale. The argument to the *callback* function will be the current position of the slider, which can range from `0` to `100`. The return value of the *callback* function should be `TCL_OK`.

`void displaySliderValue (char* window, char* name, char* value)`

This function displays a value associated with a scale's slider. The scale is identified by its name and the *window* it is in. This function must be called by the user of the slider. Only the first 6 characters of the value will be used.

14.8 Tycho Target

The CGC TychoTarget is an experimental target that provides a way to create CGC control panels that use the functionality in Tycho. A universe that uses TychoTarget must provide a script that creates the control panel that the user sees. The TychoTarget is documented in `$PTOLEMY/demo/whats_new/whats_new0.7/tychotarget.html`.

Chapter 15. CG56 Domain

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15.1 Introduction

The CG56 domain generates assembly code for the Motorola 56001 processor. Chapter 13 describes the features common to all code generation domains. The basic principles of writing code generation stars are explained in section 13.2. You will find explanations for codeblocks, macros, and attributes there. This chapter explains features specific to the CG56 domain. Refer to the CG56 chapter in the user manual for an introduction to these domains.

15.2 Data Types

The supported CG56 data types are:

```
int
intarray
fix
fixarray
```

In addition the `complex` data type is partially supported. None of the currently defined stars that take `anytype` input except `Fork`, are compatible with the `complex` data type. It would be possible to write a star that supports a complex token read into an `anytype` input. To do this the star writer would have to check on the input type and make sure to do the intended function on both the X and Y memory components of the complex input token.

15.3 Attributes

In addition to the code generation attributes detailed in 13.2.6, for CG56 attributes are defined to specify the X and Y memory banks. They are:

`A_XMEM`	Allocate this state in X memory
`A_YMEM`	Allocate this state in Y memory

The underlying bits are `AB_XMEM`, and `AB_YMEM`. Each attribute above turns one off and turns the other on (e.g. `A_YMEM` turns `AB_YMEM` on and `AB_XMEM` off).

Also for CG56 stars, portholes can assert attributes `P_XMEM` and `P_YMEM`, which work in exactly the same way as `A_XMEM` and `A_YMEM`. The default attribute for a 56001 porthole is `P_XMEM`, which allocates the porthole buffer in X memory. Specifying the `P_YMEM` attribute places the porthole buffer in Y memory.

15.4 Code Streams

The CG56 domain uses the default assembly language code streams discussed in “Assembly code streams” on page 13-17. There are few target specific code streams detailed by target below.

15.4.1 Sim56Target Code Streams

`simulatorCmds`
: Collects the commands to configure the Motorola DSP simulator.

`shellCmds`
: Collects the commands that will be used in a shell script to start the run. The resultant script simply invokes the simulator with the file generated from `simulatorCmds`.

15.4.2 S56XTarget/S56XTargetWH Code Streams

`aioCmds`
: Collects the GUI specification which is interpreted by `qdm` or `gslider`.

`shellCmds`
: Collects the commands that will be used in a shell script to start the run. The resultant script can start qdm or gslider. In the case of the S56XTarget, it might also download and run the generated code on the S-56X dsp card.

Chapter 16. C50 Domain

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16.1 Introduction

The C50 domain generates assembly code for the Texas Instruments C5x series of processors. Chapter 13 describes the features common to all code generation domains. The basic principles of writing code generation stars are explained in section 13.2. You will find explanations for codeblocks, macros, and attributes there. This chapter explains features specific to the C50 domain. Refer to the C50 chapter in the *Ptolemy User's Manual* for an introduction to these domains.

16.2 Data Types

The supported CG50 data types are:

```
int
intarray
fix
fixarray
```

In addition the `complex` data type is supported for portholes (but not states). A `complex` number is stored as a sequence of two 16 bit numbers. The real part is stored at the lower address.

16.3 Attributes

In addition to the code generation attributes detailed in 13.2.6, for C50 attributes are defined to specify the Single Access RAM and Double Access RAM memory banks. They are:

`A_BMEM`	Allocate this state in the address range specified by the *bMemMap* target parameter.
`A_UMEM`	Allocate this state in the address range specified by the *uMemMap* target parameter.

The underlying bits are `AB_BMEM`, and `AB_UMEM`. Each attribute above turns one off and turns the other on (e.g. `A_BMEM` turns `AB_BMEM` on and `AB_UMEM` off).

Also for C50 stars, portholes can assert attributes `P_BMEM` and `P_UMEM`, which work in exactly the same way as `A_BMEM` and `A_UMEM`. The default attribute for a C50 porthole is `P_BMEM`, which allocates the porthole buffer in DARAM memory. Specifying the `P_UMEM` attribute places the porthole buffer in SARAM memory.

16.4 Code Streams

The C50 domain uses the default assembly language code streams discussed in "Assembly code streams" on page 13-17. Additionally, TITarget declares a code stream

named `TISuProcs` to store code that should be placed outside the main loop. Note that the code stored in this code stream will get added after the `wrapup` methods of the stars have been called. The `TISuProcs` code stream is useful for adding procedures when using non-COFF assemblers (like the TI DSK assembler) or defining tables of coefficients in program memory (as an example, the C50 instruction `macd` needs one of the operands to be in program memory)

16.5 Symbols

The DSKC50 targets defines certain symbols that are meant to be unique. They are `AIC_INIT, SETUPX, SETUPR, XINT, RINT and TINT`. The C50Sin star defines a global symbol `SINTBL` used to store a sine table that is shared by all C50Sin stars. The user should avoid redefining these symbols in the output assembly file.

16.6 Reserved Memory

The DSKC50 target reserves the last 9 words in DARAM block 1 to store data needed to configure the Analog Interface Chip in the DSK board

Chapter 17. Creating New Domains

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17.1 Introduction

One of Ptolemy's strengths is the ability to combine heterogeneous models of computation into one system. In Ptolemy, a model of computation corresponds to a `Domain`. The code for each `Domain` interacts with the Ptolemy kernel. This overview describes the general structure of the various classes that are used by a `Domain` in its interaction with the kernel. The Ptolemy *User's Manual* has a more complete overview of this information.

A functional block, such as an adder or an FFT, is called a `Star` in Ptolemy terminology, (see "Writing Stars for Simulation" on page 2-1 for more information). A collection of connected `Stars` form a `Galaxy` (see Chapter 2 of the *User's Manual* for more information). Ptolemy supports graphical hierarchy so that an entire `Galaxy` can be formed and used as a single function block icon. The `Galaxy` can then be connected to other `Stars` or `Galaxies` to create another `Galaxy`. Usually, all the `Stars` of a `Galaxy` are from the same `Domain` but it is possible to connect `Stars` of one domain to a `Galaxy` of another domain using a `WormHole`.

A `Universe` is a complete executable system. A `Universe` can be either a single `Galaxy` or a collection of disconnected Galaxies. To run a `Universe`, each `Galaxy` also needs a `Target`. In simulation domains, a `Target` is essentially a collection of methods to compute a schedule and run the various `Stars` of a `Galaxy`. Some `Domains` have more than one possible scheduling algorithm available and the `Target` is used to select the desired scheduler. In code generation domains, a `Target` also computes a schedule and runs the individual `Stars`, but each `Star` only generates code to be executed later. Code generation `Targets` also handle compiling, loading, and running the generated code on the target architecture.

At a lower level are the connections between `Blocks`. A `Block` is a `Star` or `Galaxy`. Each `Block` has a number of input and output terminals which are attached to a `Block` through its `PortHoles`. A special `PortHole`, called a `MultiPortHole`, is used to make multiple connections but with only one terminal. Two `Blocks` are not directly connected through their `PortHoles`. Rather, their `PortHoles` are connected to an intermediary object called a `Geodesic`. In simulation domains, data is passed between `PortHoles` (through the `Geodesic`) using container objects called `Particles`. Ptolemy uses a system where `Particles` are used and recycled instead of created and deleted when needed. `Particles` are obtained from a production and storage class called a `Plasma`, which creates new `Particles` if there are no old ones to reuse. `Particles` that have completed their task are returned to the

Plasma, which may reissue them at a later request. Graphically, the Star to Star connection is depicted below:

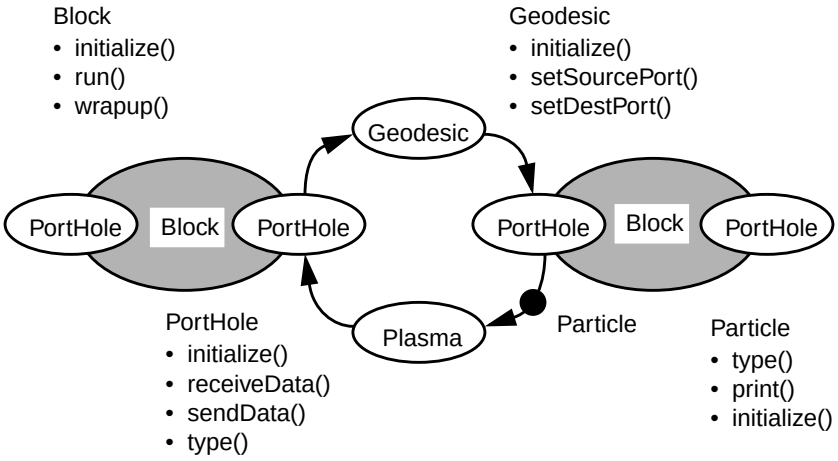

FIGURE 17-1: Block objects in Ptolemy can send and receive data encapsulated in Particles through Portholes. Buffering and transport is handled by the Geodesic and garbage collection by the Plasma. Some methods are shown.

The classes defined above provide most of the functionality necessary for a working domain. One additional class needed by all domains is a Scheduler to compute the order of execution of the Stars in the Galaxy.

Therefore, creating a new Ptolemy simulation domain will typically involve writing new classes for Stars, PortHoles, WormHoles, Targets, and Schedulers.

Creating a new domain is a fairly involved process, and not to be done lightly. The first thing that many users want to do when they see Ptolemy is create a new domain. However, it is often the case that the functionality they need is already in either the SDF or DE domains, or they can merely add a Target or Scheduler rather than an entire domain.

17.2 A closer look at the various classes

A simulation Domain can use the various classes mentioned above as they exist in the Ptolemy kernel or it can redefine them as needed. For example, in the SDF domain, the classes SDFStar, SDFPortHole, SDFScheduler, SDFDomain, SDFTarget, and SDFWormhole have all been defined. Most of those classes inherit much of their functionality from the corresponding kernel classes but the Domain creator is free to make major changes as well. The kernel Geodesic, Plasma, and Particle classes are used without modification, but other domains such as the CG domain have derived a subclass from Geodesic. The Domain creator needs to decide whether or not existing Ptolemy classes can be used without change, therefore it is a good idea to understand what functionality the kernel classes provide.

The following is a brief description of the various classes that either need to be defined or are used by a Domain. Note that we only provide a functional description of some of the major methods of each class and not a complete description of all methods.

17.2.1 Target

A Target is an object that manages the execution of the Stars in a Domain.

Major methods:

run()	Called to execute a schedule.
wrapup()	Called at the end of an execution to clean up.
setup()	Called by initialize() (which is inherited from the Block class, which is a common base class for many of Ptolemy's classes). Sets each Star to point to this Target and sets up the Scheduler.

Major objects contained are:

gal	A pointer to the Galaxy being executed.
sched	A pointer to the Scheduler that is being used.

For further information about Targets, see some of the existing domains.

17.2.2 Domain

Declares the type of various components of the Domain, like which type of WormHole, PortHole, Star, etc. is used by the Domain.

Major methods:

newWorm()	Create a WormHole of the appropriate type for this Domain.
newFrom()	Create an EventHorizon (an object that is used to interface to other Domains, used with WormHoles) that translates data from a Universal format to a Domain specific one.
newTo()	Create an EventHorizon that translates data from a Domain specific format to a Universal one.
newNode()	Returns a Geodesic of the appropriate type for this Domain.

17.2.3 Star

A Star is an object derived from class Block that implements an atomic function.

Major methods:

run()	What to do to run the star.

For example, the DataFlowStar class (a parent class to many of the dataflow domain stars such as SDFStar and DDFStar) defines this function to make each input PortHole obtain Particles from the Geodesic, execute the go() method of each Star, and then have each output PortHole put its Particles into the Geodesic.

17.2.4 PortHole

PortHoles are data members of Stars and are where streams of Particles enter or leave the Stars. Each PortHole always handles Particles of one type, so two connected PortHoles need to decide which data type they will use if they are not the same. There is a

base class called GenericPort which provides some basic methods that derived classes should redefine as well as some data members commonly needed by all PortHole types.

Major methods:

isItInput()	Return TRUE if the PortHole class is an input type.
isItOutput()	Return TRUE if the PortHole class is an output type.
isItMulti()	Return TRUE if the PortHole class is a MultiPorthole.
connect()	Connect this PortHole to a Geodesic (create one if needed) and tell that Geodesic to connect itself to both this PortHole and the destination PortHole. Also provides the number of delays on this connection.
initialize()	Initialize the PortHole. In the case of output PortHoles, this function will usually initialize the connected Geodesic as well. Resolve the type of Particles with the PortHole it is connected to.
receiveData()	What to do to receive data from the Geodesic.
sendData()	What to do to send data to the Geodesic.
putParticle()	Put a particle from the buffer into the Geodesic.
getParticle()	Get a particle from the Geodesic and put it into the buffer.
numXfer()	Returns numberTokens, the number of Particles transferred per execution.
numTokens()	Returns the number of Particles inside the Geodesic.
numInitDelays()	Returns the number of initial delay on the Geodesic.
geo()	Returns a pointer to the Geodesic this PortHole is connected to.
setDelay()	Set the delay on the Geodesic.

Major data members:

myType	Data type of particles in this porthole.
myGeodesic	The Geodesic that this PortHole is connected to
myPlasma	A pointer to the Plasma used to request new Particles.
myBuffer	Usually a CircularBuffer used to store incoming or outgoing Particles.
farSidePort	The PortHole that we are connected to.
bufferSize	The size of the Buffer.
numberTokens	The number of Particles consumed or generated each time we access the Geodesic.

Note that PortHoles are generally separated into input PortHoles and output

PortHoles. They aren't designed to handle bidirectional traffic.

17.2.5 Geodesic

Models a FIFO buffer (usually) between two PortHoles. Major methods:

setSourcePort()	Set the source PortHole and the delay on this connection. A delay is usually implemented as an initial Particle in the Geodesic's buffer, but this can be changed depending on the desired functionality.
setDestPort()	Set the destination PortHole.
disconnect()	Disconnect from the given PortHole.
setDelay()	Set the number of delays on this connection.
initialize()	Initialize the buffer in this Geodesic. This means either clear it or insert the number of initial Particles needed to match the number of delays on this connection (these Particles are taken from the source PortHoles's Plasma).
put()	Put a Particle into the buffer
get()	Get a Particle from the buffer. incCount() and decCount() are used by a Scheduler to simulate an execution.
numInit()	Return the number of initial particles.

Major data members:

originatingPort	A pointer to the source PortHole.
destinationPort	A pointer to the destination PortHole.
pstack	The buffer, implemented as a ParticleStack.
sz	The number of Particles in the buffer.
numInitialParticles	The number of initial delays.

17.2.6 Plasma

There are container object for unused Particles. There is one global instance of a Plasma for each type of Particle defined in the kernel. This class is usually only used by the Domains and not changed by the authors of new Domains.

Major methods:

put()	Return an unused Particle to the Plasma.
get()	Get an unused Particle (or create one if needed).

17.2.7 Particle

The various Particle types supported by Ptolemy. Currently, the types are Float,

Int, Complex, Fix, and Message. The Message Particle is used to carry Messages (inside Envelopes) which can be almost anything. For example, the Matrix class is transferred using Message Particles. These classes are also only used as-is by the Domains and not redefined for new domains.

17.2.8 Scheduler

Sets up the execution by determining the order in which each Star of the Galaxy will fire. Execution is performed using two main methods -- setup() and run(). Schedulers can be timed or untimed, depending on the Domain's model of execution. This class will usually be different for each domain, although some domains reuse the Scheduler of another domain, if the Scheduler is appropriate for the new domain's model of computation.

Major methods:

setup()	Checks the Stars in the Galaxy, initializes them, and creates a schedule.
run()	Run the schedule computed in setup()

Major data members

myGalaxy	The pointer to the Galaxy that the Scheduler is working on.
myTarget	The pointer to the Target which is controlling the execution.

17.3 What happens when a Universe is run

Now that you have some idea of what classes exist in the Ptolemy kernel, this section will try to explain flow of control when a Universe is run. By knowing this, you will get an idea of what additions or changes might be needed to get the functionality you desire and how the code of your new domain will fit in.

First off, a little more about the basics of Ptolemy classes. Almost every object class in Ptolemy is derived from the NamedObj class. This class simply provides support for a Name field, a longer Description field, and a pointer to a Parent Block. Also, the method initialize() is declared here to be purely virtual, so every object should have some kind of initialization function.

The Block class is derived from NamedObj and is the main base class for most actors in Ptolemy. It has I/O constructs like PortHoles and MultiPortHoles, state/parameter constructs like State, and defines execution methods such as setup(), run() and wrapup(). The Block also provides a virtual function to access an associated Scheduler.

A simulation universe is generally of type DataFlowStar. When a universe is run, the flow of control is as follows, using the SDF domain as an example:

```
PTcl::dispatcher()
      PTcl::run()
            PTcl::computeSchedule()
                  Runnable::initTarget()
                        Block::initialize()
                              SDFTarget::setup()
                                    Target::setup()
                                          SDFScheduler::setup()
```

Notice at this point that we have called two domain-specific methods, namely `SDFTarget::setup()` and `SDFScheduler::setup()`. The `Target` can have a choice of more than one `Scheduler` and in this case it called the default `SDFScheduler`. We continue here with a more detailed description of a very important function:

```
SDFScheduler::setup()
checkConnectivity()     // Checks that the galaxy is
                        //   properly connected.
  prepareGalaxy()       // Initializes the portHoles of each star and
                        //   the geodesics that connect them.
  checkStars()          // Verifies that the type of the Stars are
                        //   compatible with this Scheduler.
  repetitions()         // Solves the balance equations for the
                        //   system and calculates how many times
                        //   each star should be fired for
                        //   one iteration (specific to dataflow).
  computeSchedule()     // Compute the actual schedule
  adjustSampleRates()   // Set the number of tokens transferred
                        //   between EventHorizons if this schedule
                        //   is for a WormHole.
```

The order of various operations can be different for each scheduler. For example, a new domain may require that the `PortHole`s be initialized after the repetitions were calculated but before the schedule was computed. The domain writer may wish to define a new function `prepareForScheduling()` that would call the `setup()` function of each `Star` without initializing the `Star`'s `PortHole`s.

Expanding `prepareGalaxy()` in more detail:

```
SDFScheduler:: prepareGalaxy()
 galaxy()->initialize()       // Initialize the galaxy.
  InterpGalaxy::initialize()  // Causes the initialization of delays
                              // and the setup of bus widths.
   Galaxy::initSubblocks()    // Calls initialize() of each star.
    DataFlowStar::initialize()// This is a general initialize.
                              // function for data flow stars.
                              //   Your own Star class might
                              //   redefine it. Sets the number
                              //   of input Ports and clears
                              //   some parameters.
     Block::initialize()      // Initializes the PortHoles and States
                              //   of the Block/Star. Calls the user
                              //   defined setup() function of each
                              //   star after the portholes and
                              //   geodesics have been initialized.
      PortHole::initialize()  // General PortHole initialization;
                              //   again you can redefine it for a
                              //   domain specific PortHole.
                              //   Resolves the type of Particles
                              //   to be sent. Allocates a
                              //   buffer and a Plasma. Request
                              //   empty Particles from the Plasma
                              //   to initialize the buffer.
       Geodesic::initialize() // General Geodesic initialization,
```

```
                                    //   called by output PortHole only.
                                    //   Clears the buffer and adds any
                                    //   initial Particles for delays.
```

After the schedule is set up and all the actors in the `Universe` have been initialized, the flow of control is as follows:

```
PTcl::run()
 PTcl::computeSchedule()      // Described above.
  PTcl::cont()
   universe->setStopeTime()   // Used to set the number of
                              //   iterations to be run.
    universe->run()
     InterpUniverse::run()
      Runnable::run()
       target->run()
        sched->run()
         SDFScheduler::run()  // The domain specific Scheduler's
                              //   run() function.
```

Let's look at what a typical scheduler does when it runs a star.

```
SDFScheduler::run()           // Checks if there has been an error
                              //   in the last iteration. Calls
                              //   runOnce() for each iteration.
 runOnce()                    //   Goes through each Star on the
                              //   schedule (which is a list of Stars
                              //   computed by setup() ) and calls
                              //   star->run().
  star->run()
   DataFlowStar::run()        // The SDF domain uses the general
                              //   DataFlowStar
                              //   run() function. A new Domain
                              //   might want to redefine this.
    ..Ports->receiveData()    // Calls receiveData() for each of
                              //   the PortHoles for this Star.
                              //   Output PortHoles would do nothing
                              //   in this case but input PortHoles
                              //   would get Particles from the
                              //   Geodesic.
    Star::run()
     SimControl::doPreActions()// Execute pre-actions for a star.
     go()                     // Call the Star specific go() function
                              //   that will process the input data
                              //   and generate data to be put in the
                              //   output PortHoles.
     SimControl::doPostActions() // Execute post-actions for a star
     ..Ports->sendData()      // Calls sendData() for each of the
                              //   PortHoles for this Star.
                              //   Input PortHoles would do nothing
                              //   in this case but output PortHoles
                              //   would put their Particles into
                              //   the Geodesic and refill their
                              //   buffers with empty Particles
                              //   from the Plasma.
```

17.4 Recipe for writing your own domain

This section describes some of the template files we have made so that you don't have to start coding from scratch. We also discuss which classes and methods of those classes that a new domain must define.

17.4.1 Introduction

The first thing to do is to think through what you want this domain to do. You should have some idea of how the your `Star`s will exchange data and what kind of `Scheduler` is needed. You should also understand the existing Ptolemy domains so that you can decide whether your domain can reuse some of the code that already exists. Also, read Chapter 1 so you understand the general classes in the Ptolemy kernel and how the domain methods interact.

17.4.2 Creating the files

The `mkdom` script at `$PTOLEMY/bin/mkdom` can be used to generate template files for a new domain. `mkdom` takes one argument, the name of the domain, which case insensitive, `mkdom` converts the what ever you pass to it as a domain name to upper and lower case internally. Here, we assume that you have set up a parallel development tree, as documented in chapter 1, or you are working in the directory tree where Ptolemy was untar'd.

1. To use `mkdom`, create a directory with the name of your domain in the `src/domains` directory. In this example, we are creating a domain called `yyy`:

```
mkdir $PTOLEMY/src/domains/yyy
```

2. cd to that directory and then run `mkdom`:

```
cd $PTOLEMY/src/domains/yyy
$PTOLEMY/bin/mkdom yyy
```

17.4.3 Required classes and methods for a new domain

`mkdom` will create copies of key files in `$PTOLEMY/src/domains/yyy/kernel` and a `Nop` star in `$PTOLEMY/src/domains/yyy/stars`. The template files have various comments about which methods you need to redefine. The template files also define many function for you automatically. If you aren't clear as to how to define the methods in each class, it is best to try look at the existing Ptolemy domains as examples.

YYY`Domain.cc` This file will be setup for you automatically so that you shouldn't need to modify much. The various methods here return `WormHoles` and `EventHorizons` which should be defined in *YYY*`Wormhole`. A node is usually a type of `Geodesic` that allows multiple connections, such as `AutoForkNode`. You can define your own *YYY*`Geodesic` or simply use the kernel's `AutoForkNode` if that is suitable (this is what SDF does).

YYY`Wormhole.{h,cc}` Various methods to interface your new domain with others must be defined if you wish to use your domain with other domains.

However, if you don't need to mix domains, then you may skip these files. Wormholes translate different notions of time or concurrency. Since some domains are timed (like DE) and others are not (like SDF), you must be able to convert from one to another.

YYY`Geodesic.{h,cc}`
: Currently we set the `Geodesic` to be the kernel's `AutoForkNode`. If the kernel's `Geodesic` class offers all the functionality you need, then this doesn't need to be changed. Otherwise try looking at some of the pre-existing domains for examples.

YYY`PortHole.{h,cc}`
: Define input `PortHole`s and output `PortHole`s, as well as `MultiPortHole`s, specific to your domain. The only required methods are generated for you, but you'll likely want to define many more support methods. Look at the kernel `PortHole`, `DFPortHole`, and `SDFPortHole` for examples.

YYY`Star.{h,cc}`
: `Domain`-specific class definition. Again, all the required methods have been defined but you'll want to add much more. Refer to `Star`, `DataFlowStar`, and `SDFStar` as examples.

YYY`Scheduler.{h,cc}`
: This is where much of the action goes. You'll need to define the function `setup()`, `run()`, and `setStopTime()`.

17.4.4 Building an object directory tree

Ptolemy can support multiple machine architectures from one source tree, the object files from each architecture go into `$PTOLEMY/obj.$PTARCH` directories. Currently, there are two ways to build the `$PTOLEMY/obj.$PTARCH` directory tree: `MAKEARCH` and `mkPtolemyTree`. To build object files for your new domain in `$PTOLEMY/obj.$PTARCH`, you will have to set up either or both of these ways. Typically, you first use `MAKEARCH` because it can operate on an existing Ptolemy tree, and once everything works, then you and other users run `mkPtolemyTree` to setup parallel development trees on the new domain.

MAKEARCH

`$PTOLEMY/MAKEARCH` is a `/bin/csh` script that creates or updates the object tree in an already existing Ptolemy tree. To add a domain to `MAKEARCH`, edit the file and look for a similar domain, and add appropriately. A little trial and error may be necessary, but the basic idea is simple: `MAKEARCH` traverses directories and creates subdirectories as it sees fit. Note that if `MAKEARCH` is under version control, you may need to do `chmod a+x MAKEARCH` when you check it back out, or it won't be executable.

Continuing with our example:

3. Edit `MAKEARCH` and add your domain yyy to the list of experimental domains:

```
set EXPDOMAINS=(cg56 cgc vhdlb vhdl mdsdf hof ipus yyy)
```

This will cause a `stars` and `kernel` directory to be created in `$PTOLEMY/obj.$PTARCH/domains/yyy` when `MAKEARCH` is run.

4. Run `MAKEARCH`:

```
cd $PTOLEMY; csh -f MAKEARCH
```

If you get a message like:

```
cxh@watson 181% csh -f MAKEARCH
making directory /users/ptolemy/obj.sol2/domains/yyy
mkdir: Failed to make directory "yyy"; Permission denied
yyy: No such file or directory
```

The you may need to remove your `obj.$PTARCH` tree, as `MAKEARCH` has probably traversed down a parallel tree created by `mkPtolemyTree` and come up in a directory that you do not own.

mkPtolemyTree

`$PTOLEMY/bin/mkPtolemyTree` is a `tclsh` script that creates a new parallel Ptolemy tree. Note that `mkPtolemyTree` cannot be run in an already existing Ptolemy development tree. The file `$PTOLEMY/mk/stars.mk` controls what directories `mkPtolemyTree` creates, you need not actually edit the `mkPtolemyTree` script. To create `pigiRpc` binaries with your new domain in it, you will need to modify `stars.mk`, so adding support for `mkPtolemyTree` is fairly trivial.

$PTOLEMY/mk/stars.mk

Follow the style for domain addition that you see in this file for the other domains. A few things to keep in mind:

- You should list the new domain before any other domain library that the new domain depends on.
- You should make sure to define the make variables to pull in other domain libraries as necessary. You may need `MDSDF=1` definition for example.
- `mkPtolemyTree` uses the `CUSTOM_DIRS` makefile variable to determine what directories to create, so be sure to add your directories here.

Continuing with our example of adding the yyy domain:

5. Edit `$PTOLEMY/mk/stars.mk` and add your entry:

```
YYYDIR = $(CROOT)/src/domains/cg56
ifdef YYY
      CUSTOM_DIRS += $(YYYDIR)/kernel $(YYYDIR)/stars
      # Have to create this eventually
      PALETTES += PTOLEMY/src/domains/yyy/icons/main.pal
      STARS += $(LIBDIR)/yyystars.o
      LIBS += -lyyystars -lyyy
      LIBFILES += $(LIBDIR)/libyyystars.$(LIBSUFFIX) \
            $(LIBDIR)/libyyy.$(LIBSUFFIX)
endif
```

$PTOLEMY/mk/ptbin.mk

In `$PTOLEMY/mk/ptbin.mk`, add your domain to the `FULL` definition. This causes your domain to be built in whenever a full `pigiRpc` binary is created.

Building a pigiRpc

6. To build a `pigiRpc` with your domain, first build and install your domain's kernel and star libraries:

```
cd $PTOLEMY/obj.$PTARCH/domains/yyy
make depend
make install
```

   If your domain depends on other domains, you will have to build in those directories as well. You may find it easier to do `cd $PTOLEMY; make install`, though this could take 3 hours. An alternative would be to create a parallel directory tree using `mkPtolemyTree`.

7. If you have not recompiled from scratch, or run `mkPtolemyTree`, you may also need to do:

```
cd $PTOLEMY/obj.$PTARCH/pigilib; make ptkRegisterCmds.o
```

8. Then build your `pigiRpc`. You can either build a full `pigiRpc` with all of the domains, or you can create a `override.mk` in `$PTOLEMY/obj.$PTARCH/pigiRpc` which will pull in only the domains you want.

   `$PTOLEMY/obj.$PTARCH/pigiRpc/override.mk` could contain:

```
YYY=1
DEFAULT_DOMAIN=YYY
USERFLAGS=
VERSION_DESC="YYY Domain Only"
```

   To build your binary, do:

```
cd $PTOLEMY/obj.$PTARCH/pigiRpc; make
```

   If you don't have all the libraries built, you may get an error message:

```
make: *** No rule to make target `../../lib.sol2/libcg56dspstars.so',
needed by `pigiRpc'. Stop.
```

   The workaround is to do:

```
cd $PTOLEMY/obj.$PTARCH/pigiRpc; make PIGI=pigiRpc
```

9. See "Creating a pigiRpc that includes your own stars" on page 1-7 for details on how to use your new pigiRpc binary.

10. To verify that your new domain has been installed, start `pigi` with the `-console` option:

```
cd $PTOLEMY; pigi -rpc $PTOLEMY/obj.$PTARCH/pigiRpc/pigiRpc -console
```

and then type:

```
domains
```

into the console window prompt. Below is the sample output for the yyy example domain:

```
pigi> domains
YYY
pigi> knownlist
Nop
pigi>
```

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