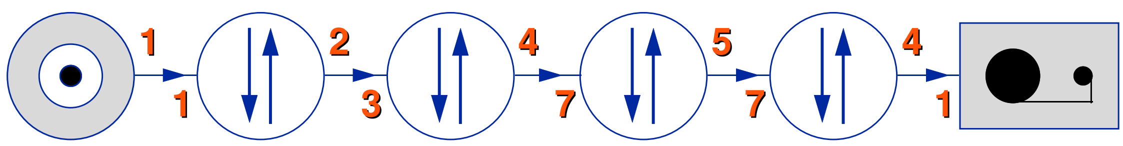
Synchronous Dataflow

- Well-suited to multirate signal processing



$$\begin{bmatrix} 1 & -1 & 0 & 0 & 0 & 0 \\ 0 & 2 & -3 & 0 & 0 & 0 \\ 0 & 0 & 4 & -7 & 0 & 0 \\ 0 & 0 & 0 & 5 & -7 & 0 \\ 0 & 0 & 0 & 0 & 4 & -1 \end{bmatrix} \times \begin{bmatrix} 147 \\ 147 \\ 98 \\ 56 \\ 40 \\ 160 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

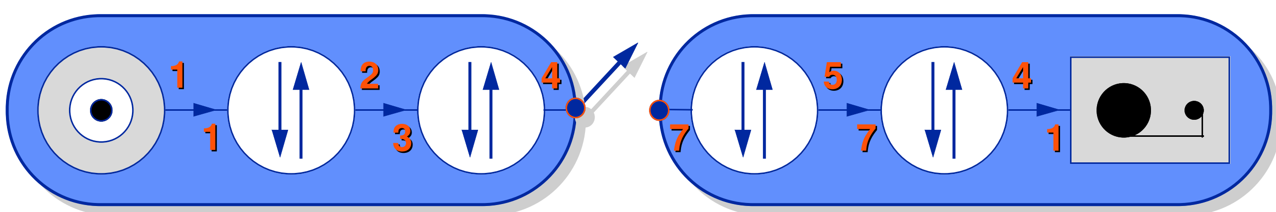
Static Scheduling

Synchronous communication with a fixed number of tokens transferred

- Balance equations determine repetitions
- Periodic schedule is computed statically

Independent Dataflow Graphs

- Tasks are described by dataflow graphs
  - Periodic schedules are computed statically



$$\begin{bmatrix} 1 & -1 & 0 \\ 0 & 2 & -3 \end{bmatrix} \times \begin{bmatrix} 3 \\ 3 \\ 2 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \qquad \begin{bmatrix} 5 & -7 & 0 \\ 0 & 4 & -1 \end{bmatrix} \times \begin{bmatrix} 7 \\ 5 \\ 20 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

Dynamic Scheduling

Asynchronous communication between independent tasks

- Repetition rates are not known exactly
- Dynamic, run-time scheduling is required

Preemptive Real-Time Scheduling

- Fixed priorities
  - – Limited processor utilization 70%
  - + Simple, efficient implementation
  - + Graceful degradation in overload situations
- Dynamic priorities
  - + Better processor utilization 100%
  - – Complex implementation
  - – Unpredictable behavior in overload situations

Rate-Monotonic Scheduling

- Periodic tasks are independent

  T_i Period

  C_i Execution time
- Rate-monotonic priority assignment is optimal: $T_1 \le T_2 \le \cdots \le T_N$
  - Only periods T_i are needed for scheduling
  - Execution times C_i are needed only to prove feasibility
  - Best-effort scheduling with imprecise execution times

Processor Utilization Bound

$$\forall i \in [1 \cdots N] \quad \min_{(k,l) \in R_i} \sum_{j=1}^{i} \frac{C_j}{lT_k} \left\lceil \frac{lT_k}{T_j} \right\rceil \leq 1$$

$$R_i = \left\{ (k,l) \,\middle|\, 1 \leq k \leq i, 1 \leq l \leq \left\lfloor T_i / T_k \right\rfloor \right\}$$

Priority Inheritance Protocols

- **Periodic tasks contend for exclusive access to shared resources**

  B_i **Blocking time**

- **Processor utilization bound**

$$\forall i \in [1 \cdots N] \min_{(k,l) \in R_i} \sum_{j=1}^{i-1} \frac{C_j}{lT_k} \left\lceil \frac{lT_k}{T_j} \right\rceil + \frac{C_i}{lT_k} + \frac{B_i}{lT_k} \leq 1$$

Non-Preemptive Scheduling

- CPU is a shared resource
- Blocking time is the execution time of one sub-task

$$B_i = \max_{(j,k)\in S_i} C_{j,k}$$

$$S_i = \left\{ (j,k) \,\middle|\, i+1 \le j \le N, 1 \le k \le N_j \right\}$$

- Accounting for context switch costs

$$B_i = 2\Delta + \max_{(j,k)\in S_i} C_{j,k}$$

Multithreaded Architectures

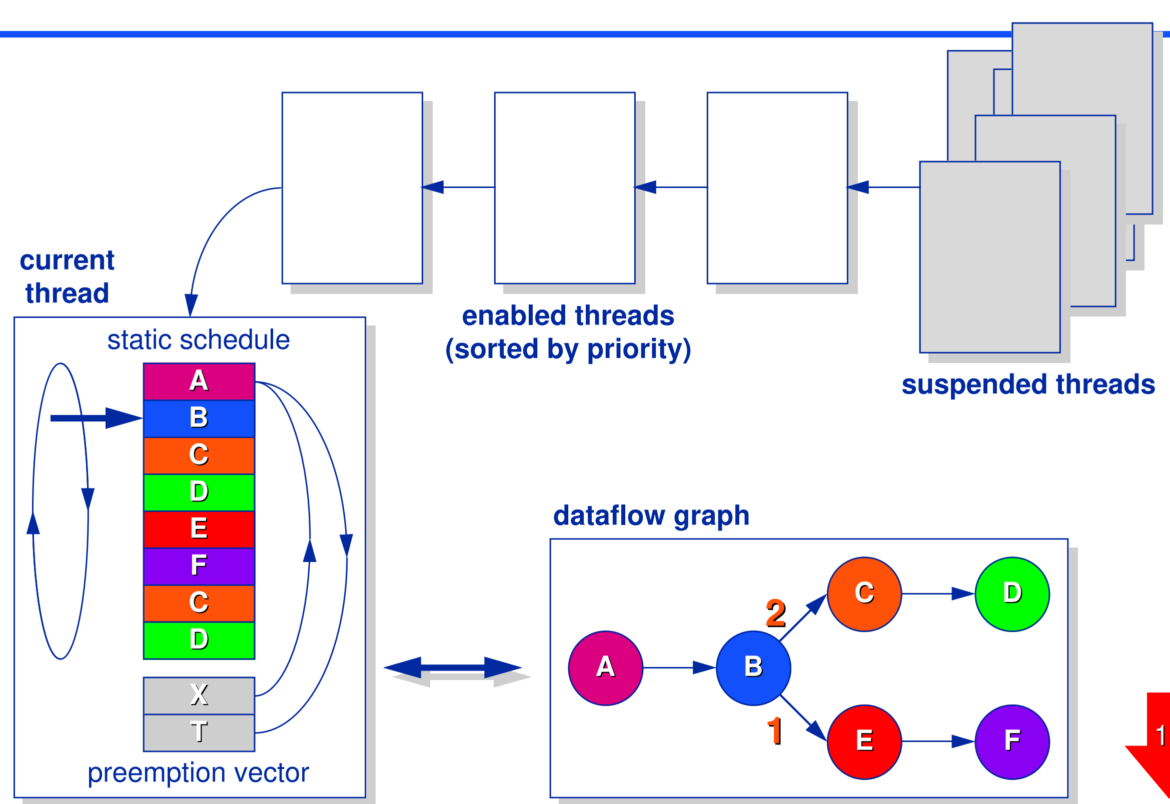
- Massively parallel, general-purpose architectures
  - High communication latency
  - Synchronization
- Hybrid Dataflow/von Neumann machines
  - Tolerate latency
  - Exploit pipelines and caches

  Examples: TAM, *T

Real-Time Extensions to TAM

- Static, periodic schedule replaces the dynamic continuation vector
- Tasks may yield control after any sub-task instead of running until the continuation vector is empty
- Tasks are prioritized

Real-Time Multithreaded Execution



Hybrid Static/Dynamic Scheduling

- Static, periodic schedules for each independent dataflow graph
- Dynamic, non-preemptive rate-monotonic scheduling for system of periodic tasks

Conclusions

- Sufficient conditions for feasible non-preemptive scheduling
- Efficient real-time execution model

Future Work

- Exact characterization of non-preemptive rate-monotonic scheduling
- Explore other system representations
  - Cyclo-static dataflow to reduce blocking times
  - Clustering to reduce run-time scheduling overhead