Dataflow Languages

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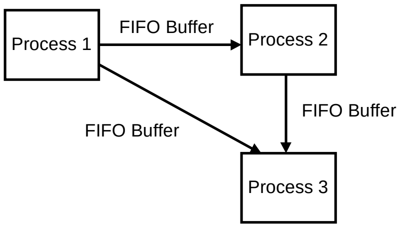
Philosophy of Dataflow Languages

- **Drastically different way of looking at computation**
- **Von Neumann imperative language style: program counter is king**
- **Dataflow language: movement of data the priority**
- **Scheduling responsibility of the system, not the programmer**

Dataflow Language Model

- **Processes communicating through FIFO buffers**



Dataflow Languages

- **Every process runs simultaneously**
- **Processes can be described with imperative code**
- **Compute … compute … receive … compute … transmit**
- **Processes can *only* communicate through buffers**

Dataflow Communication

- **Communication is *only* through buffers**
- **Buffers usually treated as unbounded for flexibility**
- **Sequence of tokens read guaranteed to be the same as the sequence of tokens written**
- **Destructive read: reading a value from a buffer removes the value**
- **Much more predictable than shared memory**

Dataflow Languages

- **Once proposed for general-purpose programming**
- **Fundamentally concurrent: should map more easily to parallel hardware**
- **A few lunatics built general-purpose dataflow computers based on this idea**
- **Largely a failure: memory spaces anathema to the dataflow formalism**

Applications of Dataflow

- Not a good fit for, say, a word processor
- Good for signal-processing applications
- Anything that deals with a continuous stream of data

- Becomes easy to parallelize
- Buffers typically used for signal processing applications anyway

Applications of Dataflow

- Perfect fit for block-diagram specifications
  - Circuit diagrams
  - Linear/nonlinear control systems
  - Signal processing

- Suggest dataflow semantics

- Common in Electrical Engineering

- Processes are blocks, connections are buffers

Kahn Process Networks

- Proposed by Kahn in 1974 as a general-purpose scheme for parallel programming
- Laid the theoretical foundation for dataflow
- Unique attribute: deterministic

- Difficult to schedule
- Too flexible to make efficient, not flexible enough for a wide class of applications
- Never put to widespread use

Kahn Process Networks

- Key idea:

Reading an empty channel blocks until data is available

- No other mechanism for sampling communication channel’s contents
  - Can’t check to see whether buffer is empty
  - Can’t wait on multiple channels at once

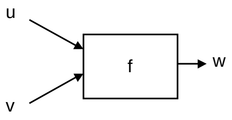
Kahn Processes

- A C-like function (Kahn used Algol)
- Arguments include FIFO channels
- Language augmented with send() and wait() operations that write and read from channels

A Kahn Process

- From Kahn’s original 1974 paper

```
process f(in int u, in int v, out int w)
{
  int i; bool b = true;
  for (;;) {
    i = b ? wait(u) : wait(w);
    printf("%i\n", i);
    send(i, w);
    b = !b;
  }
}
```



Process alternately reads from u and v, prints the data value, and writes it to w

A Kahn Process

- **From Kahn’s original 1974 paper**

```
process f(in int u, in int v, out int w)
{
  int i; bool b = true;
  for (;;) {
    i = b ? wait(u) : wait(w);
    printf("%i\n", i);
    send(i, w);
    b = !b;
  }
}
```

Process interface includes FIFOs

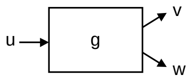
wait() returns the next token in an input FIFO, blocking if it’s empty

send() writes a data value on an output FIFO

A Kahn Process

- **From Kahn’s original 1974 paper**

```
process g(in int u, out int v, out int w)
{
  int i; bool b = true;
  for(;;) {
    i = wait(u);
    if (b) send(i, v); else send(i, w);
    b = !b;
  }
}
```

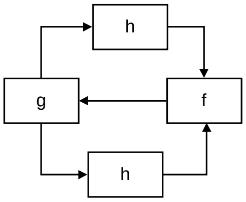


Process reads from u and alternately copies it to v and w

A Kahn System

- **Prints an alternating sequence of 0’s and 1’s**

Emits a 1 then copies input to output



Emits a 0 then copies input to output

Proof of Determinism

- **Because a process can’t check the contents of buffers, only read from them, each process only sees sequence of data values coming in on buffers**
- **Behavior of process:**

Compute … read … compute … write … read … compute

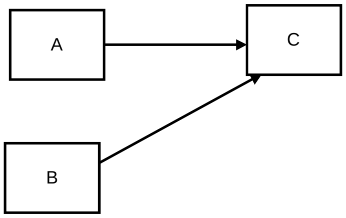
- **Values written only depend on program state**
- **Computation only depends on program state**
- **Reads always return sequence of data values, nothing more**

Determinism

- **Another way to see it:**
- **If I’m a process, I am only affected by the sequence of tokens on my inputs**
- **I can’t tell whether they arrive early, late, or in what order**
- **I will behave the same in any case**
- **Thus, the sequence of tokens I put on my outputs is the same regardless of the timing of the tokens on my inputs**

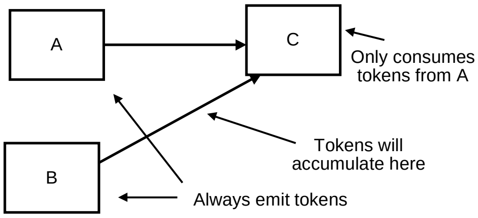
Scheduling Kahn Networks

- **Challenge is running processes without accumulating tokens**



Scheduling Kahn Networks

- Challenge is running processes without accumulating tokens



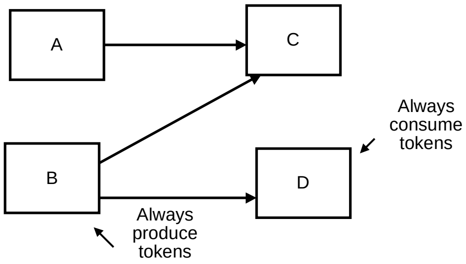
Only consumes tokens from A

Tokens will accumulate here

Always emit tokens

Demand-driven Scheduling?

- Apparent solution: only run a process whose outputs are being actively solicited
- However...

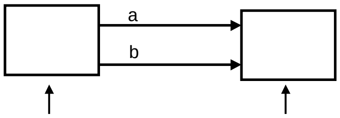


Always consume tokens

Always produce tokens

Other Difficult Systems

- Not all systems can be scheduled without token accumulation



Produces two a's for every b

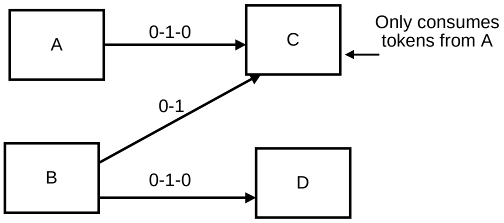
Alternates between receiving one a and one b

Tom Parks' Algorithm

- Schedules a Kahn Process Network in bounded memory if it is possible
- Start with bounded buffers
- Use any scheduling technique that avoids buffer overflow
- If system deadlocks because of buffer overflow, increase size of smallest buffer and continue

Parks' Algorithm in Action

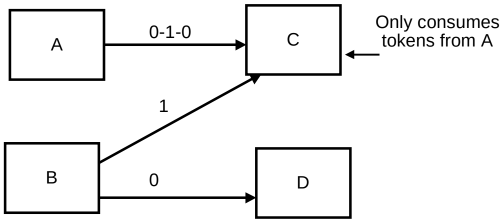
- Start with buffers of size 1
- Run A, B, C, D



Only consumes tokens from A

Parks' Algorithm in Action

- B blocked waiting for space in B->C buffer
- Run A, then C
- System will run indefinitely



Only consumes tokens from A

Parks' Scheduling Algorithm

- **Neat trick**
- **Whether a Kahn network can execute in bounded memory is undecidable**
- **Parks' algorithm does not violate this**
- **It will run in bounded memory if possible, and use unbounded memory if necessary**

Using Parks' Scheduling Algorithm

- **It works, but…**
- **Requires dynamic memory allocation**
- **Does not guarantee minimum memory usage**
- **Scheduling choices may affect memory usage**
- **Data-dependent decisions may affect memory usage**
- **Relatively costly scheduling technique**
- **Detecting deadlock may be difficult**

Kahn Process Networks

- **Their beauty is that the scheduling algorithm does not affect their functional behavior**
- **Difficult to schedule because of need to balance relative process rates**
- **System inherently gives the scheduler few hints about appropriate rates**
- **Parks' algorithm expensive and fussy to implement**
- **Might be appropriate for coarse-grain systems**
  - **Scheduling overhead dwarfed by process behavior**

Synchronous Dataflow (SDF)

- **Edward Lee and David Messerschmitt, Berkeley, 1987**
- **Restriction of Kahn Networks to allow compile-time scheduling**
- **Basic idea: each process reads and writes a fixed number of tokens each time it fires:**

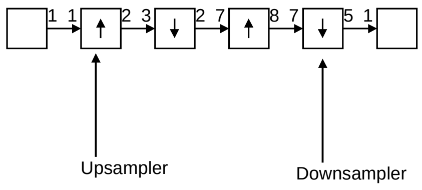
```
loop
  read 3 A, 5 B, 1 C … compute … write 2 D, 1 E, 7 F
end loop
```

SDF and Signal Processing

- **Restriction natural for multirate signal processing**
- **Typical signal-processing processes:**
- **Unit-rate**
  - **Adders, multipliers**
- **Upsamplers (1 in, n out)**
- **Downsamplers (n in, 1 out)**

Multi-rate SDF System

- **DAT-to-CD rate converter**
- **Converts a 44.1 kHz sampling rate to 48 kHz**

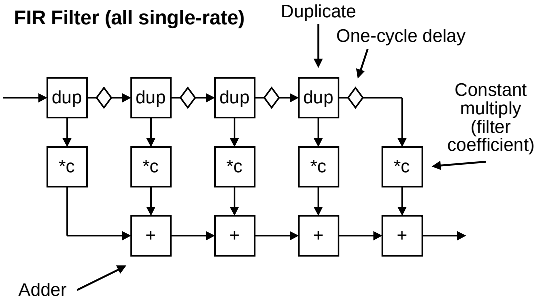


Delays

- Kahn processes often have an initialization phase
- SDF doesn't allow this because rates are not always constant
- Alternative: an SDF system may start with tokens in its buffers
- These behave like delays (signal-processing)
- Delays are sometimes necessary to avoid deadlock

Example SDF System

- FIR Filter (all single-rate)



SDF Scheduling

- Schedule can be determined completely before the system runs
- Two steps:

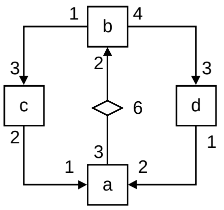
1. Establish relative execution rates by solving a system of linear equations
2. Determine periodic schedule by simulating system for a single round

SDF Scheduling

- Goal: a sequence of process firings that
- Runs each process at least once in proportion to its rate
- Avoids underflow
  - no process fired unless all tokens it consumes are available
- Returns the number of tokens in each buffer to their initial state
- Result: the schedule can be executed repeatedly without accumulating tokens in buffers

Calculating Rates

- Each arc imposes a constraint



$3a - 2b = 0$

$4b - 3d = 0$

$b - 3c = 0$

$2c - a = 0$

$d - 2a = 0$

Solution:

$a = 2c$

$b = 3c$

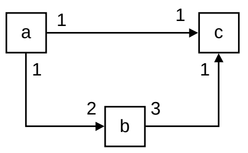
$d = 4c$

Calculating Rates

- Consistent systems have a one-dimensional solution
  - Usually want the smallest integer solution
- Inconsistent systems only have the all-zeros solution
- Disconnected systems have two- or higher-dimensional solutions

An Inconsistent System

- No way to execute it without an unbounded accumulation of tokens
- Only consistent solution is “do nothing”



a – c = 0

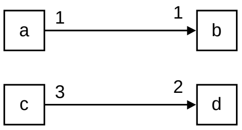
a – 2b = 0

3b – c = 0

3a – 2c = 0

An Underconstrained System

- Two or more unconnected pieces
- Relative rates between pieces undefined

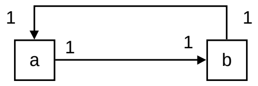


a – b = 0

3c – 2d = 0

Consistent Rates Not Enough

- A consistent system with no schedule
- Rates do not avoid deadlock



- Solution here: add a delay on one of the arcs

SDF Scheduling

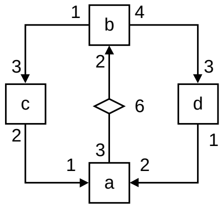
- Fundamental SDF Scheduling Theorem:

If rates can be established, any scheduling algorithm that avoids buffer underflow will produce a correct schedule if it exists

Scheduling Example

- Theorem guarantees any valid simulation will produce a schedule

a=2 b=3 c=1 d=4



Possible schedules:

BBBCDDDDAA

BDBDBCADDA

BBDDBDDCAA

… many more

BC … is not valid

Scheduling Choices

- SDF Scheduling Theorem guarantees a schedule will be found if it exists
- Systems often have many possible schedules
- How can we use this flexibility?
  - Reduced code size
  - Reduced buffer sizes

SDF Code Generation

- Often done with prewritten blocks
- For traditional DSP, handwritten implementation of large functions (e.g., FFT)
- One copy of each block’s code made for each appearance in the schedule
  - I.e., no function calls

Code Generation

- In this simple-minded approach, the schedule

BBBCDDDDAA

would produce code like

```
B;
B;
C;
D;
D;
D;
D;
A;
A;
```

Looped Code Generation

- Obvious improvement: use loops
- Rewrite the schedule in “looped” form:

(3 B) C (4 D) (2 A)

- Generated code becomes

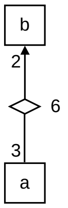
```
for ( i = 0 ; i < 3; i++) B;
C;
for ( i = 0 ; i < 4 ; i++) D;
for ( i = 0 ; i < 2 ; i++) A;
```

Single-Appearance Schedules

- Often possible to choose a looped schedule in which each block appears exactly once
- Leads to efficient block-structured code
  - Only requires one copy of each block’s code
- Does not always exist
- Often requires more buffer space than other schedules

Finding Single-Appearance Schedules

- Always exist for acyclic graphs
  - Blocks appear in topological order
- For SCCs, look at number of tokens that pass through arc in each period (follows from balance equations)
- If there is at least that much delay, the arc does not impose ordering constraints
- Idea: no possibility of underflow



a=2 b=3

6 tokens cross the arc

delay of 6 is enough

Finding Single-Appearance Schedules

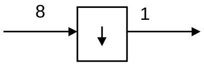
- Recursive strongly-connected component decomposition
- Decompose into SCCs
- Remove non-constraining arcs
- Recurse if possible
  - Removing arcs may break the SCC into two or more

Minimum-Memory Schedules

- Another possible objective
- Often increases code size (block-generated code)
- Static scheduling makes it possible to exactly predict memory requirements
- Simultaneously improving code size, memory requirements, sharing buffers, etc. remain open research problems

Cyclo-static Dataflow

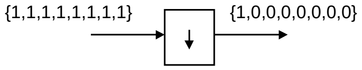
- SDF suffers from requiring each process to produce and consume all tokens in a single firing
- Tends to lead to larger buffer requirements
- Example: downsampler



- Don’t really need to store 8 tokens in the buffer
- This process simply discards 7 of them, anyway

Cyclo-static Dataflow

- Alternative: have periodic, binary firings



- Semantics: first firing: consume 1, produce 1
- Second through eighth firing: consume 1, produce 0

Cyclo-Static Dataflow

- Scheduling is much like SDF
- Balance equations establish relative rates as before
- Any scheduler that avoids underflow will produce a schedule if one exists
- Advantage: even more schedule flexibility
- Makes it easier to avoid large buffers
- Especially good for hardware implementation:
  - Hardware likes moving single values at a time

Summary of Dataflow

- Processes communicating exclusively through FIFOs
- Kahn process networks
  - Blocking read, nonblocking write
  - Deterministic
  - Hard to schedule
  - Parks’ algorithm requires deadlock detection, dynamic buffer-size adjustment

Summary of Dataflow

- Synchronous Dataflow (SDF)
- Firing rules:
  - Fixed token consumption/production
- Can be scheduled statically
  - Solve balance equations to establish rates
  - Any correct simulation will produce a schedule if one exists
- Looped schedules
  - For code generation: implies loops in generated code
  - Recursive SCC Decomposition
- CSDF: breaks firing rules into smaller pieces
  - Scheduling problem largely the same