Dataflow Languages

Languages for Embedded Systems

Prof. Stephen A. Edwards
Summer 2005
NCTU, Taiwan

Philosophy of Dataflow Languages

Drastically different way of looking at computation

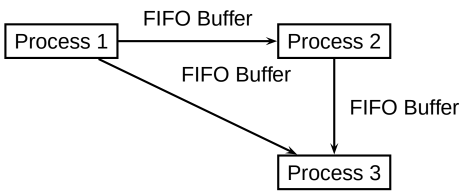
Von Neumann imperative language style: program counter is king

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

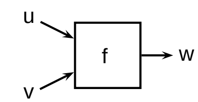
A C-like function (Kahn used Algol)

Arguments include FIFO channels

Language augmented with send() and wait() operations that write and read from channels

A Process from Kahn's 1974 paper

```
process f(in int u, in int v, out int w)
{
  int i; bool b = true;
  for (;;) {
    i = b ? wait(u) : wait(v);
    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 Process from Kahn's 1974 paper

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

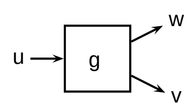
Interface includes FIFOs

wait() returns the next token in the FIFO, blocking if empty

send() writes a token into a FIFO without blocking

Another Sample Process

```
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;
  }
}
```

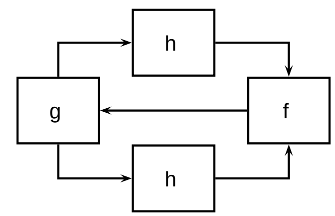


Process reads from u and alternately copies it to v and w

A Kahn System

Prints an alternating sequence of 0s and 1s

Emits a 1 then copies input to output



Emits a 0 then copies input to output

Proof of Determinism

Because a process cannot 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:

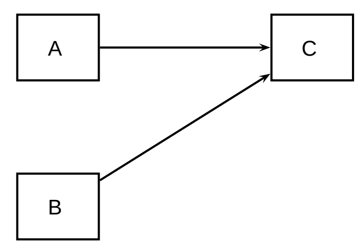
Imagine you are a process. You are only affected by the sequence of tokens on my inputs, and can't tell whether they arrive early, late, or in what order (blocking takes care of this, but you can't tell whether you blocked).

You will behave the same in any case

Thus, the sequence of tokens you put on your outputs is the same regardless of the timing of the tokens on your inputs

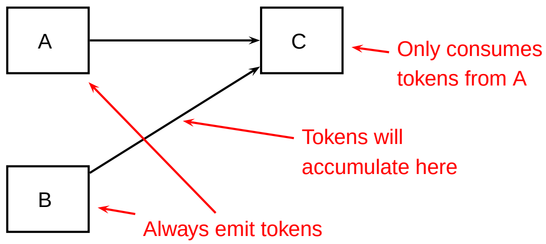
Scheduling Kahn Networks

Challenge is running processes without accumulating tokens



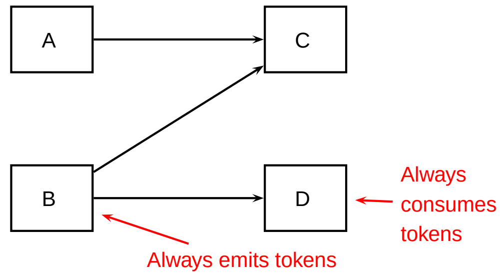
Scheduling Kahn Networks

Challenge is running processes without accumulating tokens



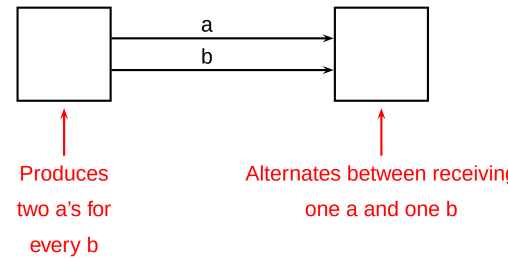
Demand-driven Scheduling?

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



Other Difficult Systems

Not all systems can be scheduled without token accumulation



Tom Parks' Algorithm

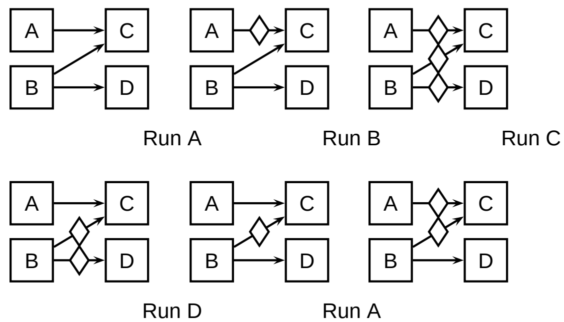
Schedules a Kahn Process Network in bounded memory if it is possible

Start with bounded buffers

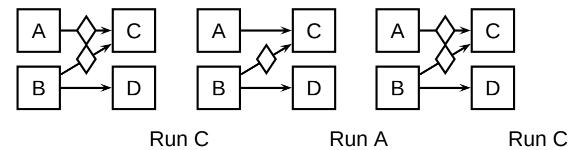
Use any scheduling technique that avoids buffer overflow

If system deadlocks because of buffer overflow, increase size of smallest buffer and continue

Parks' Algorithm in Action



Parks' Algorithm in Action



B blocked waiting for space in B→C buffer

Run A, then C, then A, then C, . . .

System will run indefinitely

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 algorithm
- 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 where 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

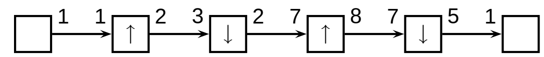
Typical signal-processing processes:

- Unit-rate
  e.g., 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



↑ Upsampler

↓ Downsampler

Delays

Kahn processes often have an initialization phase

SDF doesn't allow this because rates are not always constant

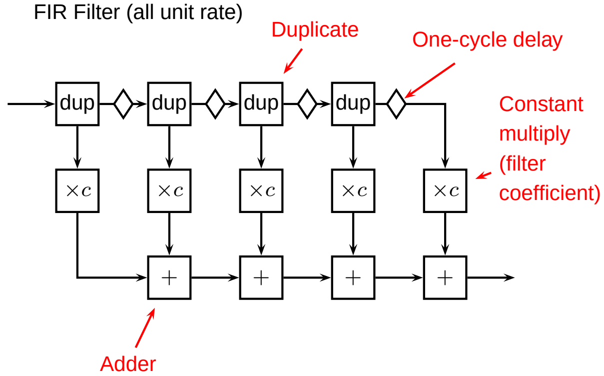
Alternative: an SDF system may start with tokens in its buffers

These behave like signal-processing-like delays

Delays are sometimes necessary to avoid deadlock

Example SDF System

FIR Filter (all unit 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

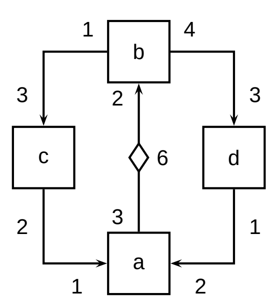
Goal: a sequence of process firings that

- 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



$$
\begin{aligned}
3a - 2b &= 0 \\
4b - 3d &= 0 \\
b - 3c &= 0 \\
2c - a &= 0 \\
d - 2a &= 0
\end{aligned}
$$

Solution:

$$
\begin{aligned}
a &= 2c \\
b &= 3c \\
d &= 4c
\end{aligned}
$$

Calculating Rates

Consistent systems have a one-dimensional solution

Usually want the smallest integer solution

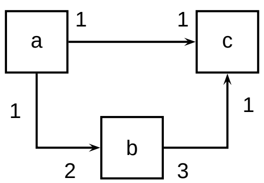
Inconsistent systems only have the all-zeros solution

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 to do nothing



$$\begin{aligned} a - c &= 0 \\ a - 2b &= 0 \\ 3b - c &= 0 \end{aligned}$$

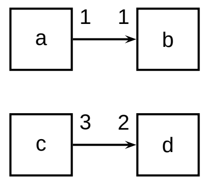
Implies

$$\begin{aligned} a - c &= 0 \\ 3a - 2c &= 0 \end{aligned}$$

An Underconstrained System

Two or more unconnected pieces

Relative rates between pieces undefined



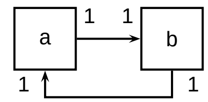
$$\begin{aligned} a - b &= 0 \\ 3c - 2d &= 0 \end{aligned}$$

Consistent Rates Are Not Enough

A consistent system with no schedule

Rates do not prevent deadlock

Solution here: add a delay on one of the arcs

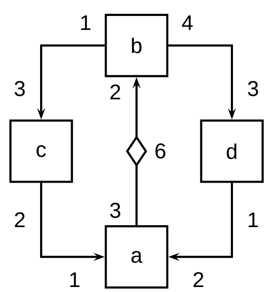


SDF Scheduling

Fundamental SDF Scheduling Theorem:

> If rates can be established, any scheduling algorithm that avoids buffer underflow will produce a correct schedule, provided one exists

Scheduling Example



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

Possible schedules:
BBBCDDDDAA
BDBDBCADDA
BBDDBDDCAA
⋮

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?

To reduce code size

To reduce buffer sizes

SDF Code Generation

Often done with prewritten blocks inlined according to the schedule

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;
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

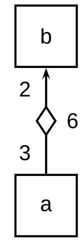
Finding SASs

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 suffices

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

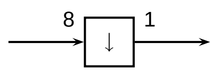
Simultaneously improving code size, memory requirements, sharing buffers, etc. remain open research problems

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

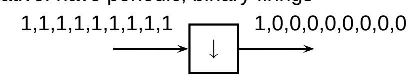


Don't really need to store 8 tokens in the buffer

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
- A correct simulation produces 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. Similar scheduling technique