Dataflow Languages

Languages for Embedded Systems

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March 2009
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

Process 1 → FIFO Buffer → Process 2 → FIFO Buffer → Process 3
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

```c
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;
    }
}
```

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

\[ A \rightarrow C \]

\[ B \rightarrow C \]
Scheduling Kahn Networks

Challenge is running processes without accumulating tokens

- A
- B
- C

- 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 emits tokens

Always consumes 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

Run A

Run B

Run C

Run D

Run A
Parks’ Algorithm in Action

Run C  Run A  Run C

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 Messerchmitt, 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
```
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)

Diagram:
- **dup**: Duplicate
- **×c**: Constant multiply (filter coefficient)
- **+**: Adder
- **One-cycle delay**
- **Duplicate**
- **Adder**
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 to do nothing

\[
\begin{align*}
    a - c &= 0 \\
    a - 2b &= 0 \\
    3b - c &= 0
\end{align*}
\]

Implies

\[
\begin{align*}
    a - c &= 0 \\
    3a - 2c &= 0
\end{align*}
\]
An Underconstrained System

Two or more unconnected pieces

Relative rates between pieces undefined

\[ a - b = 0 \]
\[ 3c - 2d = 0 \]
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

```
  a  1  1  b
  1  1  1
```
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

Possible schedules:
BBBCDDDDDDAA
BDBDBCADDA
BBDDBDDBCAA

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

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

```
BBBCDDDDDDAA
```

would produce code like

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

```plaintext
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.

\[ a = 2 \quad b = 3 \]

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

\[
1,1,1,1,1,1,1,1 \rightarrow \downarrow \rightarrow 1,0,0,0,0,0,0,0
\]

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