CS184b: Computer Architecture (Abstractions and Optimizations)

Day 16: May 12, 2003

Dataflow

Today

- Dataflow Model
- Dataflow Basics
- Examples
- Basic Architecture Requirements

Functional

- What is a functional language?
- What is a functional routine?
- Functional
  - Like a mathematical function
  - Given same inputs, always returns same outputs
  - No state
  - No side effects

Functional

Functional:

- F(x) = x * x;
- (define (f x) (* x x))
- int f(int x) { return(x * x); }

Non-Functional

Non-functional:

- (define counter 0)
  (define (next-number!)
      (set! counter (+ counter 1))
      counter)
- static int counter=0;
  int increment () { return(++counter); }

Dataflow

- Model of computation
- Contrast with Control flow

Dataflow / Control Flow

Dataflow
- Program is a graph of operators
- Operator consumes tokens and produces tokens
- All operators run concurrently

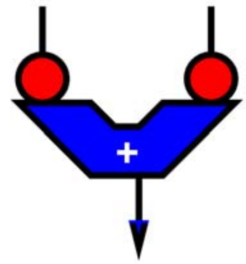
Control flow
- Program is a sequence of operations
- Operator reads inputs and writes outputs into common store
- One operator runs at a time
  - Defines successor

Token

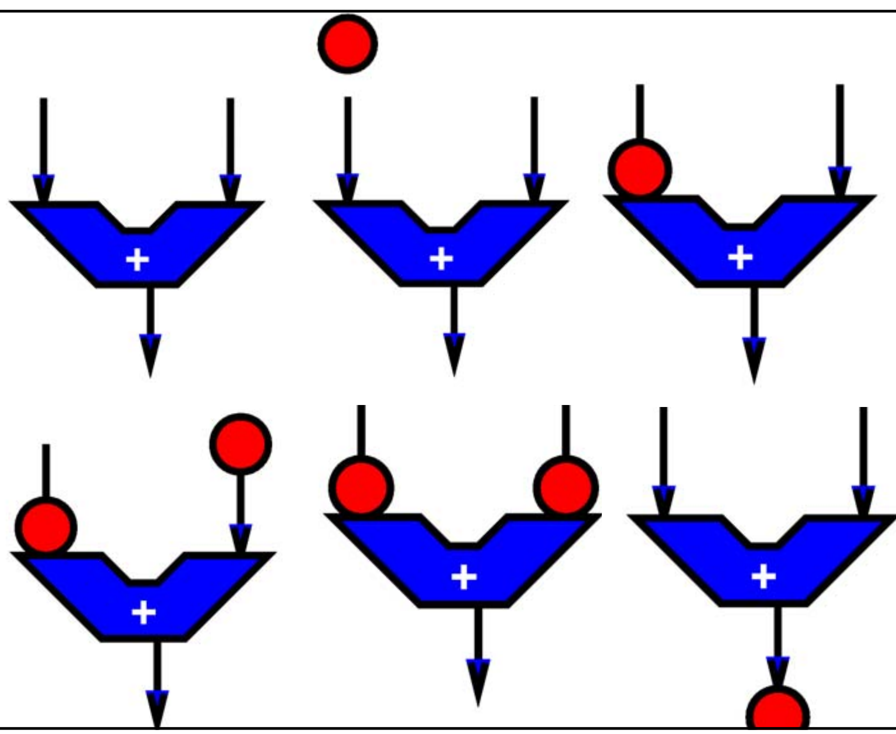
- Data value with presence indication

Operator

- Takes in one or more inputs
- Computes on the inputs
- Produces a result

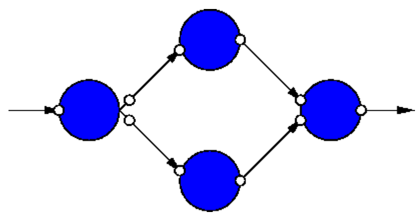


- Logically self-timed
  - "Fires" only when input set present
  - Signals availability of output

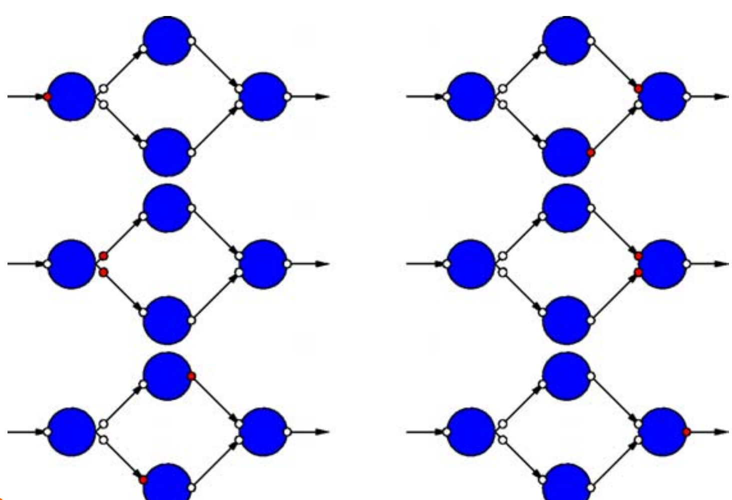


Dataflow Graph

- Represents
  - computation sub-blocks
  - linkage
- Abstractly
  - controlled by data presence



Dataflow Graph Example

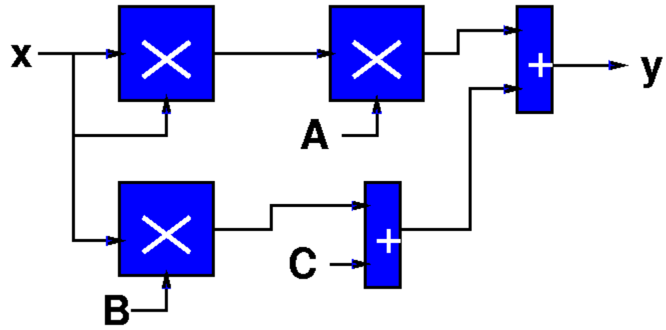


Straight-line Code

- Easily constructed into DAG
  - Same DAG saw before
  - No need to linearize

Dataflow Graph

- Real problem is a graph



Day4

Task Has Parallelism

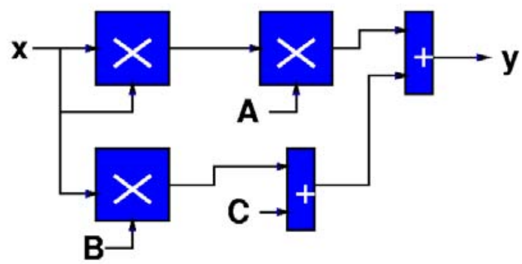
MPY R3,R2,R2

MPY R4,R2,R5

MPY R3,R6,R3

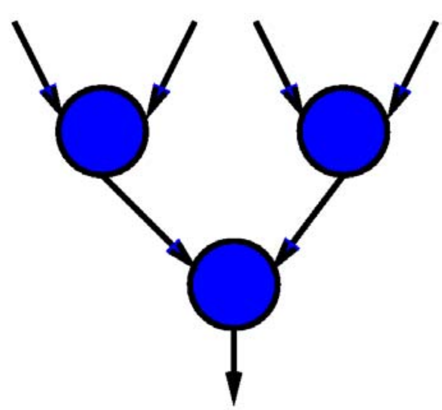
ADD R4,R4,R7

ADD R4,R3,R4



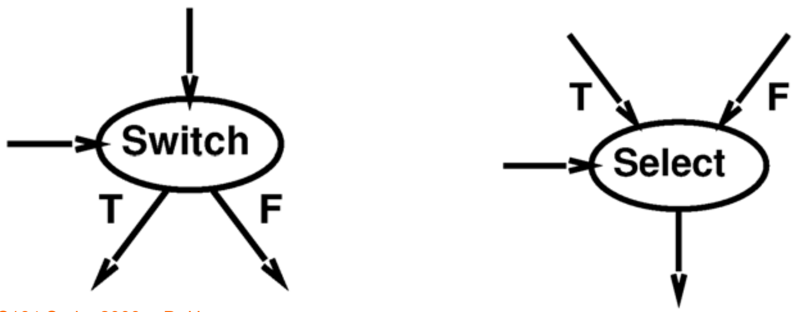
DF Exposes Freedom

- Exploit dynamic ordering of data arrival
- Saw aggressive control flow implementations had to exploit
  - Scoreboarding
  - OO issue

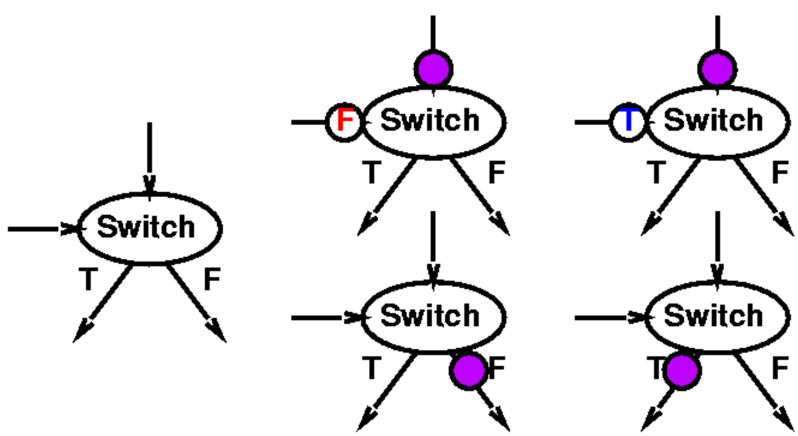


Data Dependence

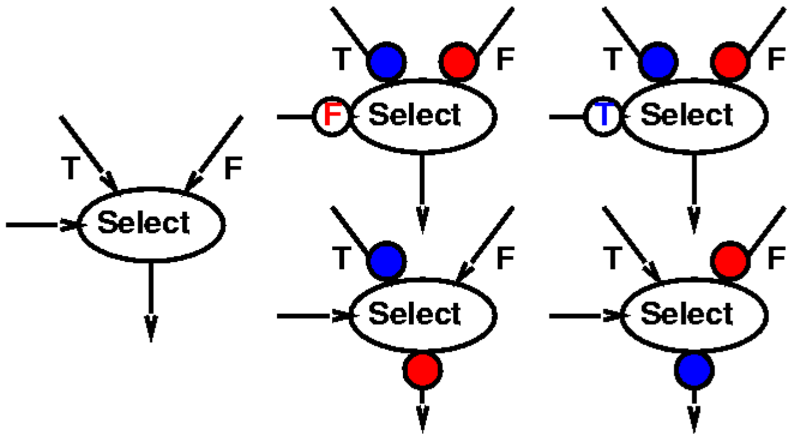
- Add Two Operators
  - Switch
  - Select



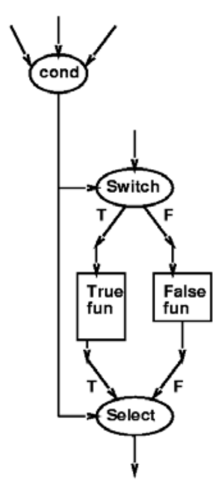
Switch



Select

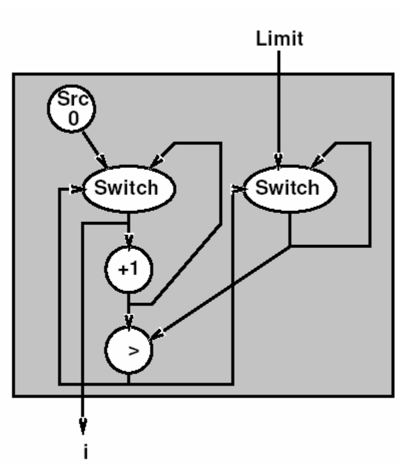


Constructing If-Then-Else



Looping

- For (i=0;i<Limit;i++)



Dataflow Graph

- Computation itself may construct / unfold parallelism
  - Loops
  - Procedure calls
    - Semantics: create a new subgraph
      - Start as new thread
      - …procedures unfold as tree / dag
      - Not as a linear stack
  - …examples shortly…

Key Element of DF Control

- Synchronization on Data Presence
- Constructs:
  - Futures (language level)
  - I-structures (data structure)
  - Full-empty bits (implementation technique)

I-Structure

- Array/object with full-empty bits on each field
- Allocated empty
- Fill in value as compute
- Strict access on empty
  - Queue requester in structure
  - Send value to requester when written and becomes full

I-Structure

- Allows efficient "functional" updates to aggregate structures
- Can pass around pointers to objects
- Preserve ordering/determinacy
- *E.g.* arrays

Future

- **Future** is a promise
- An indication that a value **will be computed**
  - And a handle for getting a handle on it
- Sometimes used as program construct

Future

- Future computation immediately returns a future
- Future is a handle/pointer to result
- (define (vmult a b)

  (cons (future (* (first a) (first b)))

  (dot (rest a) (rest b))))
- [Version for wrighton on next slide]

DF V-Mult product in C/Java

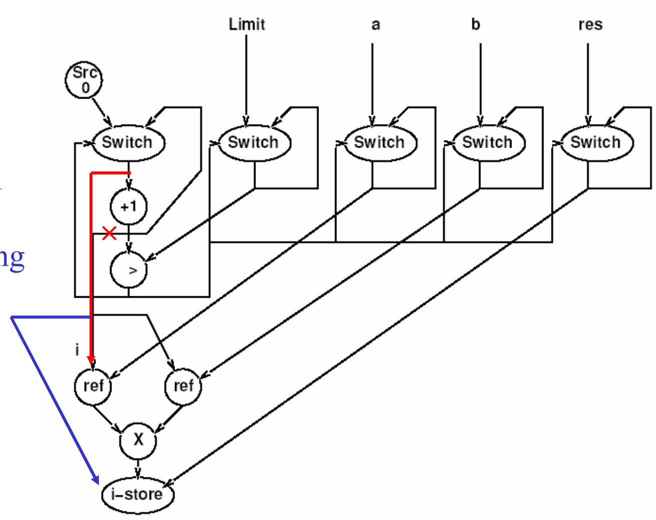
```
int [] vmult (int [] a, int [] b)
{
    // consistency check on a.length, b.length
    int [] res = new int[a.length];
    for (int i=0;i<res.length;i++)
        future res[i]=a[i]*b[i];
    – return (res);
}
// assume int [] is an I-Structure
```

I-Structure V-Mult Example

Two errors in this version:

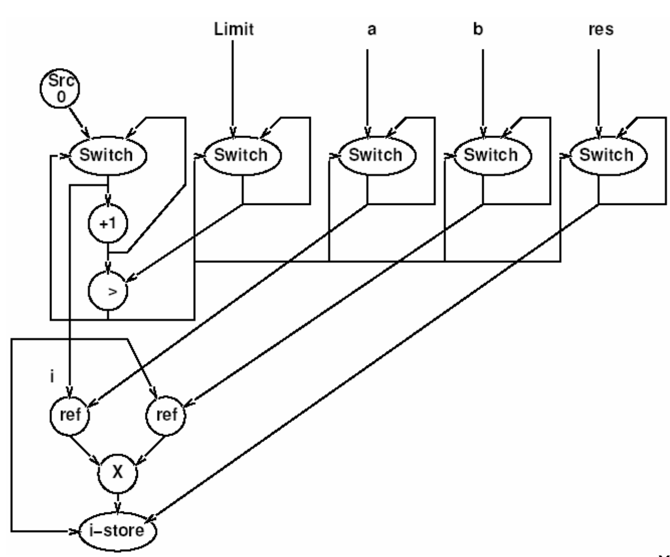
1) fencepost on value for i

2) Not delivering i to i-store



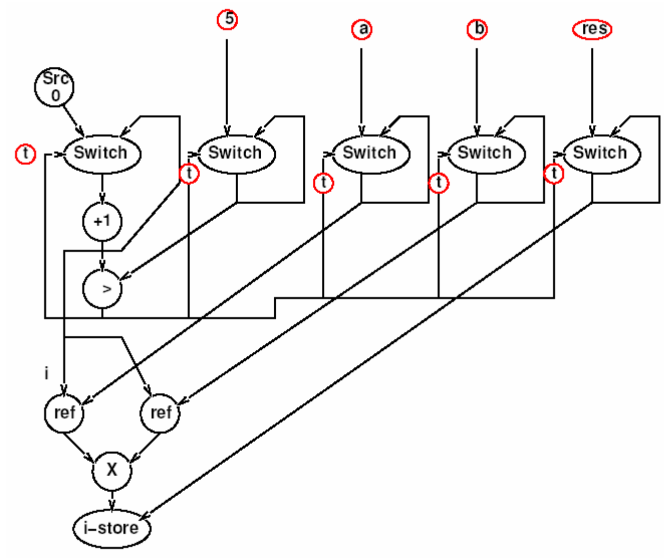
I-Structure V-Mult Example

Corrected dataflow

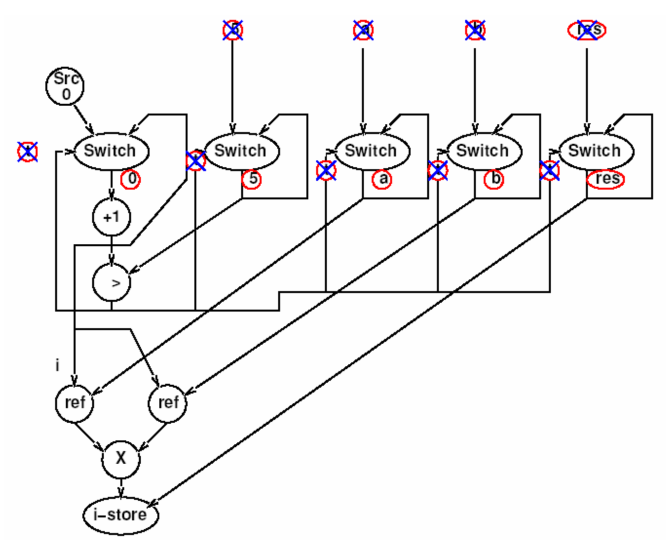


I-Structure V-Mult Example

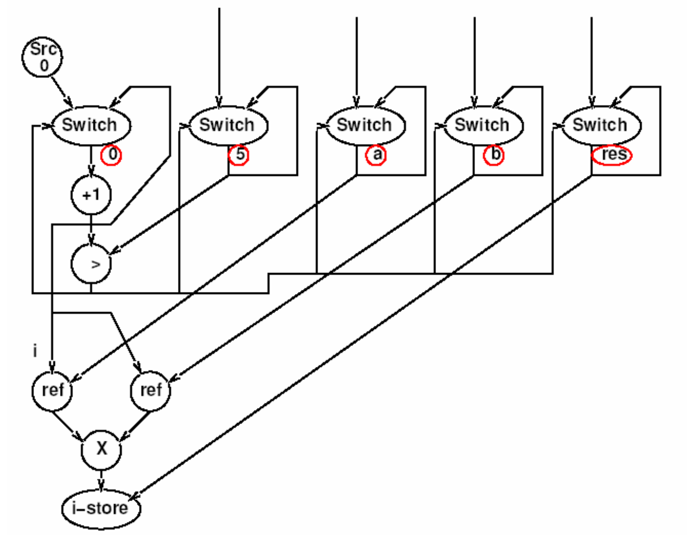
N.B.
this and remainder still have two errors.



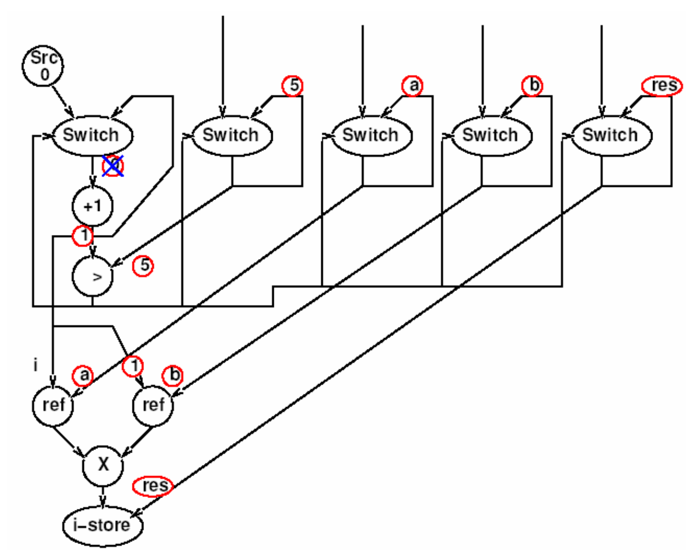
I-Structure V-Mult Example



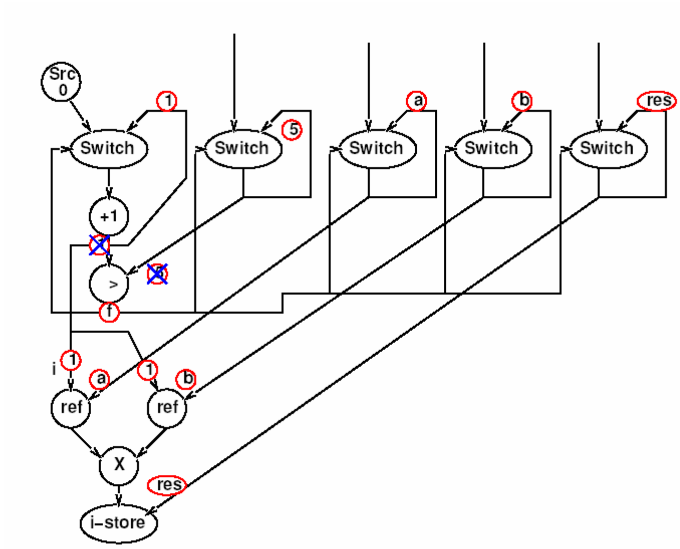
I-Structure V-Mult Example



I-Structure V-Mult Example



I-Structure V-Mult Example



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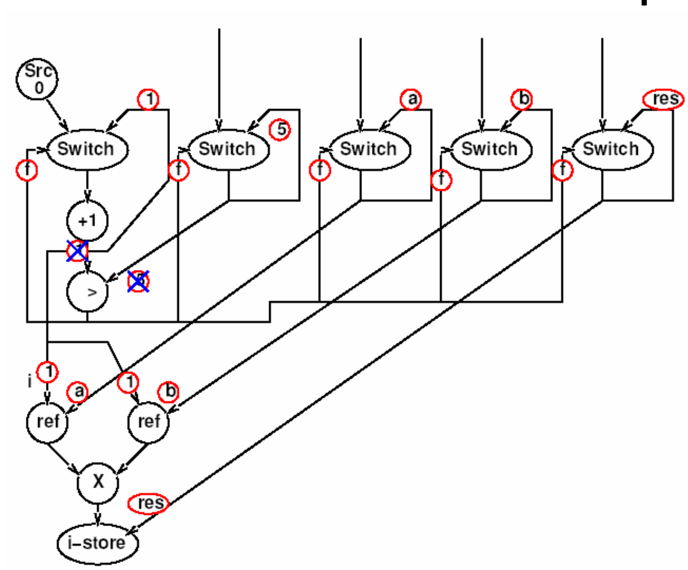

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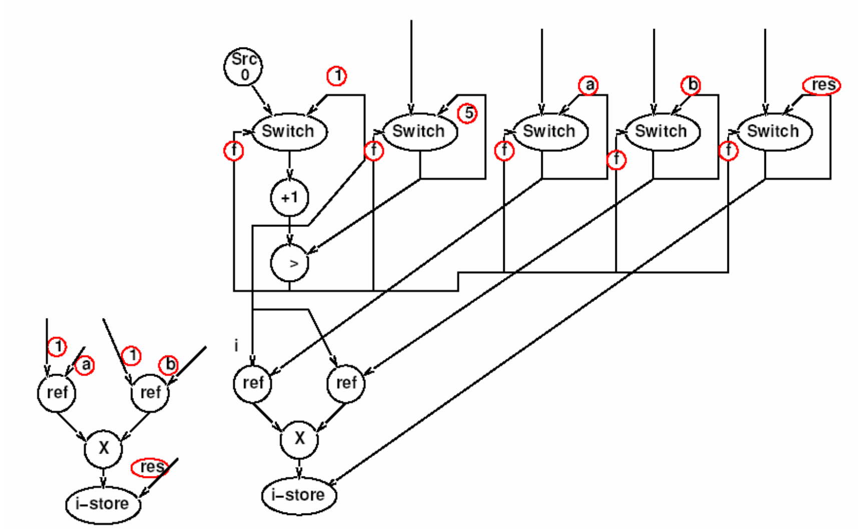

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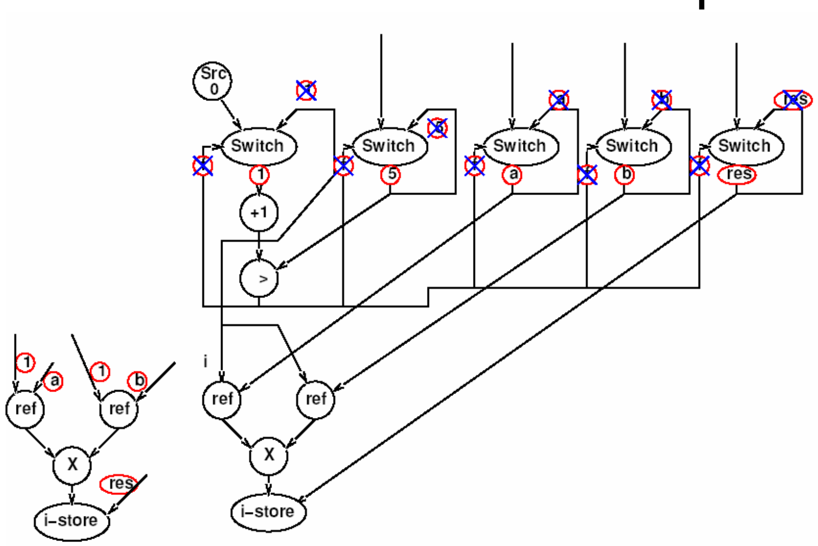

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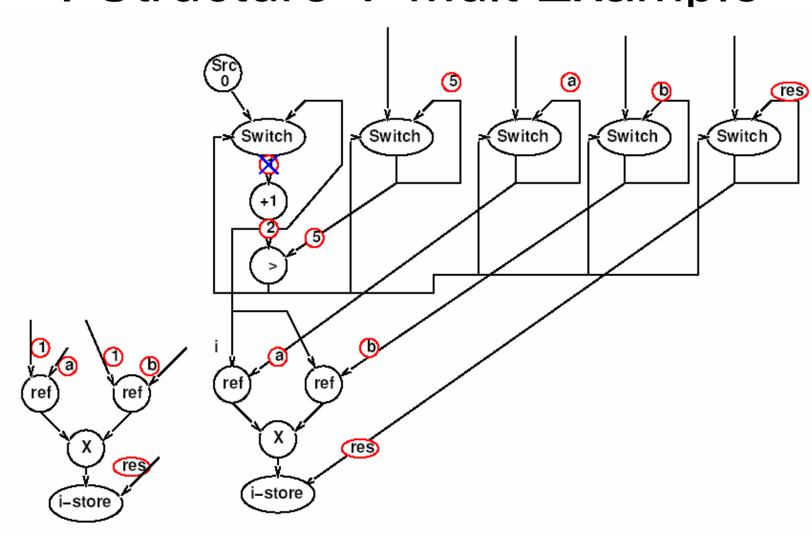

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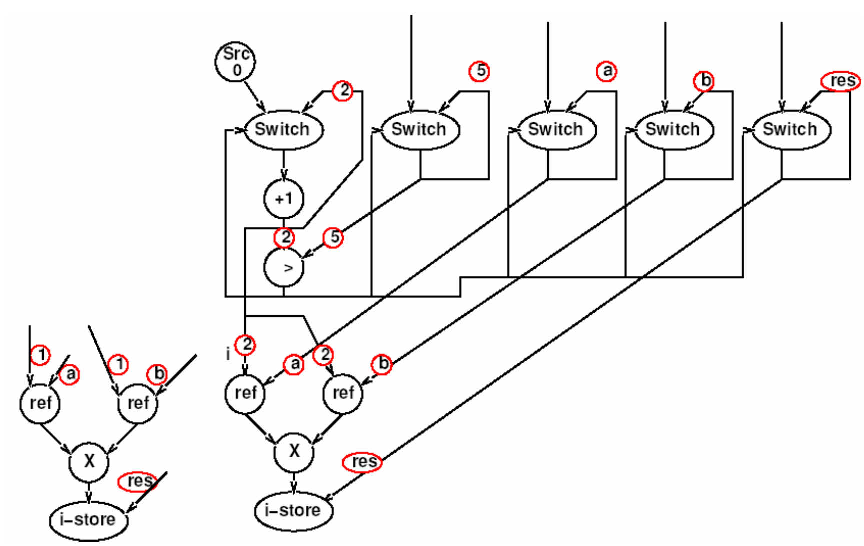

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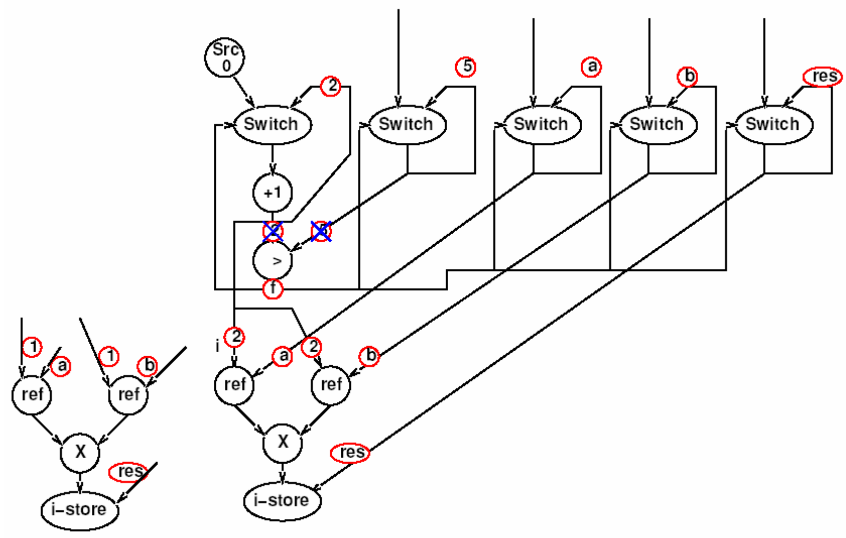

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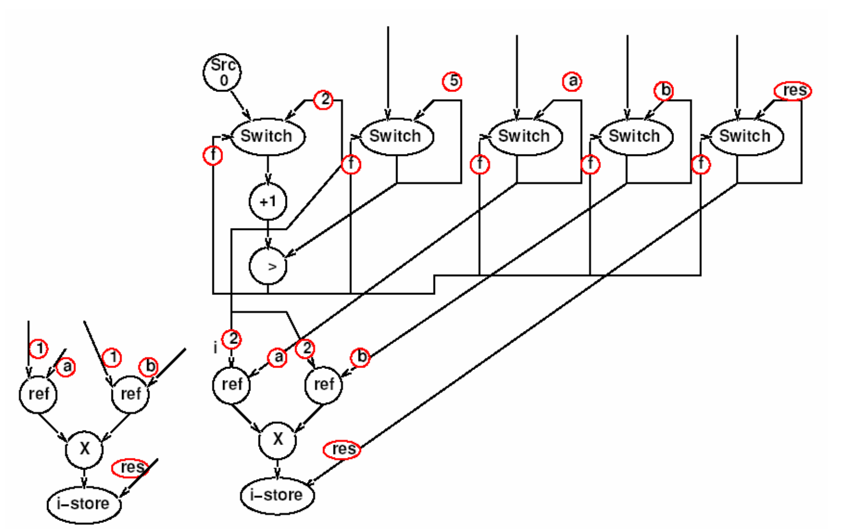

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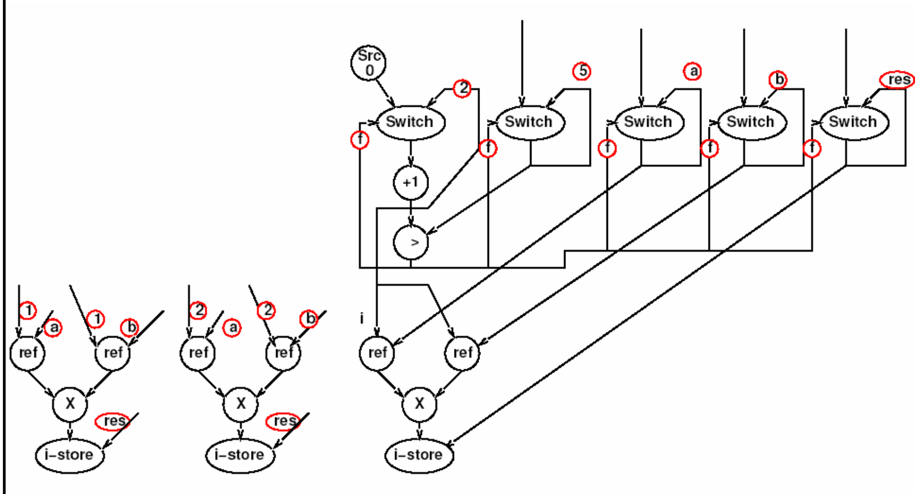
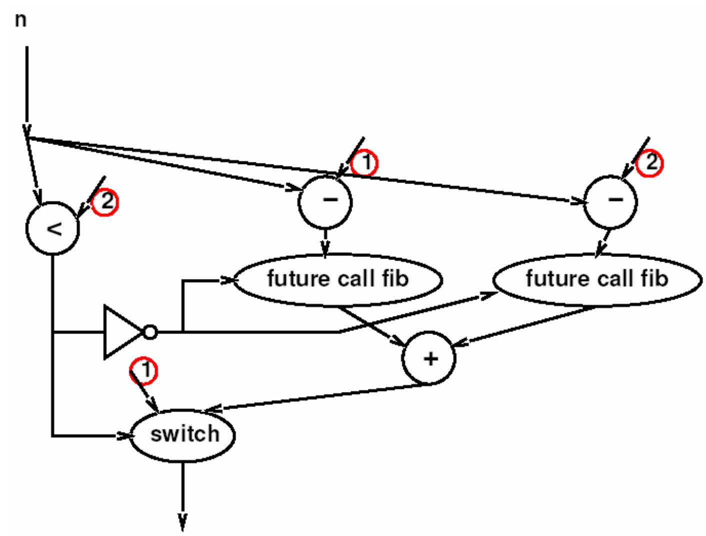


Fib

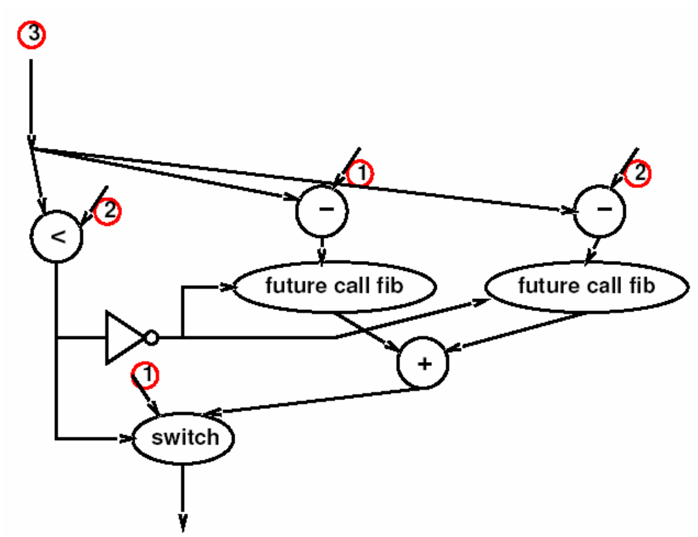
```
(define (fib n)
    (if (< n 2) 1 (+ (future (fib (- n 1)))
                     (future (fib (- n 2))))))
```

```
int fib(int n)
{
    if (n<2)
       return(1);
    else
      return ((future)fib(n-1) + (future)fib(n-2));
}
```

Fibonacci Example



Fibonacci Example



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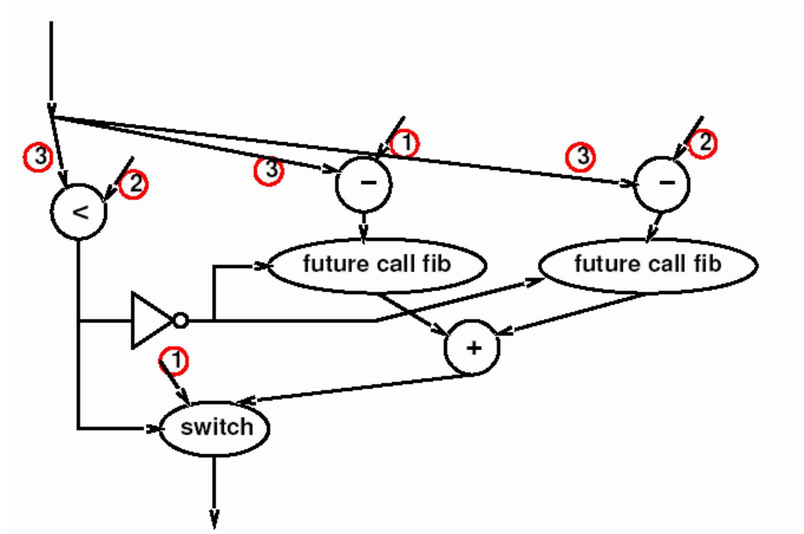

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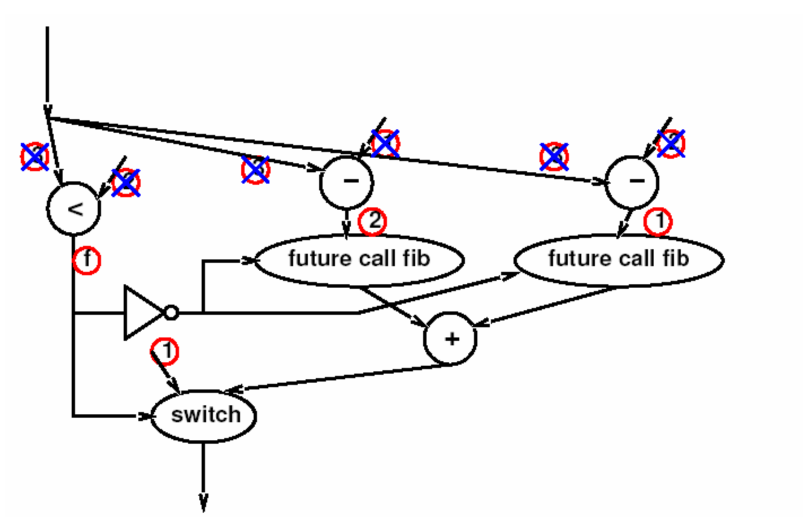

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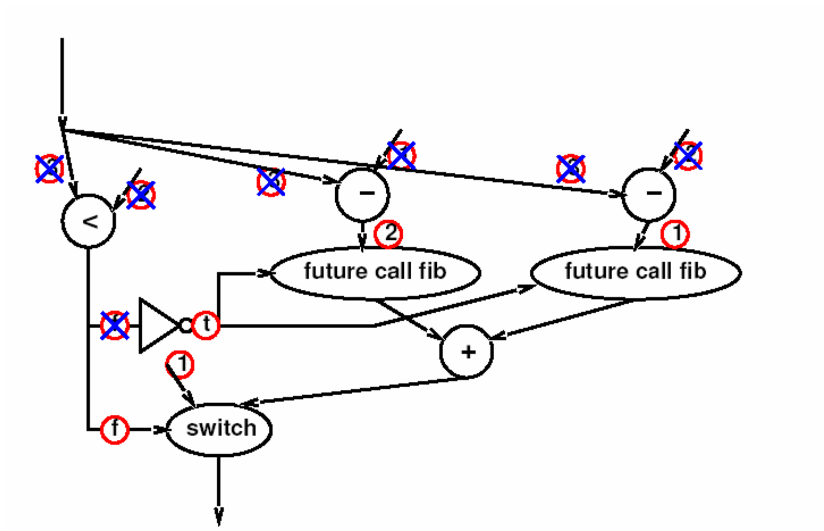

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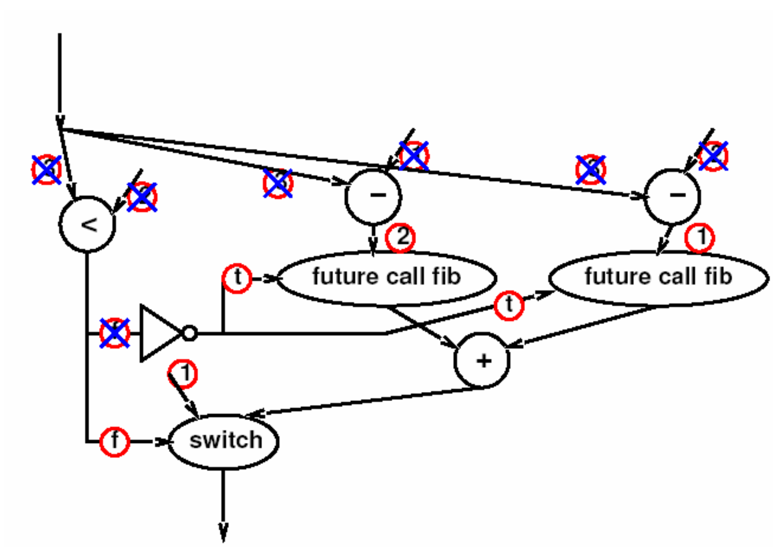

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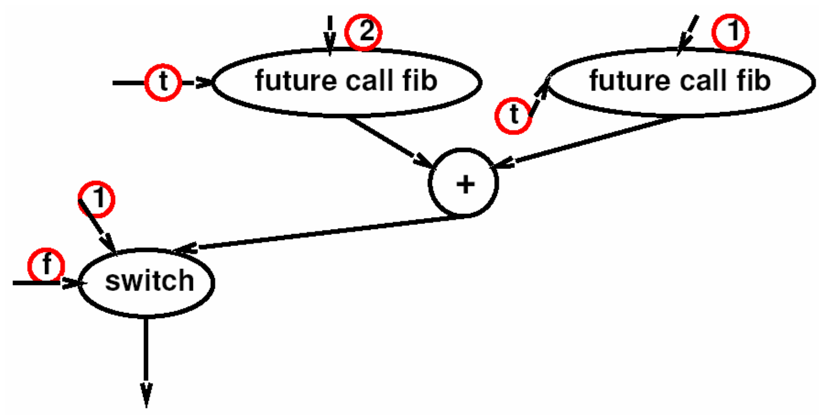
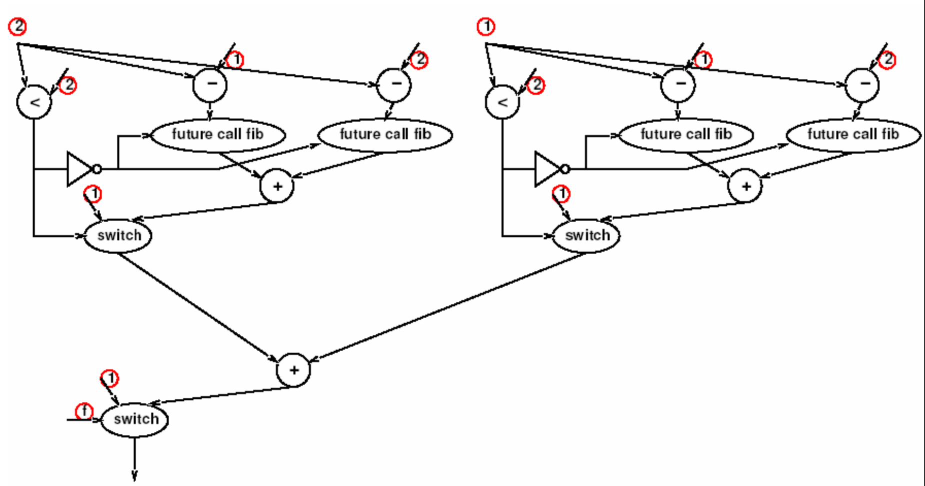


Fibonacci Example



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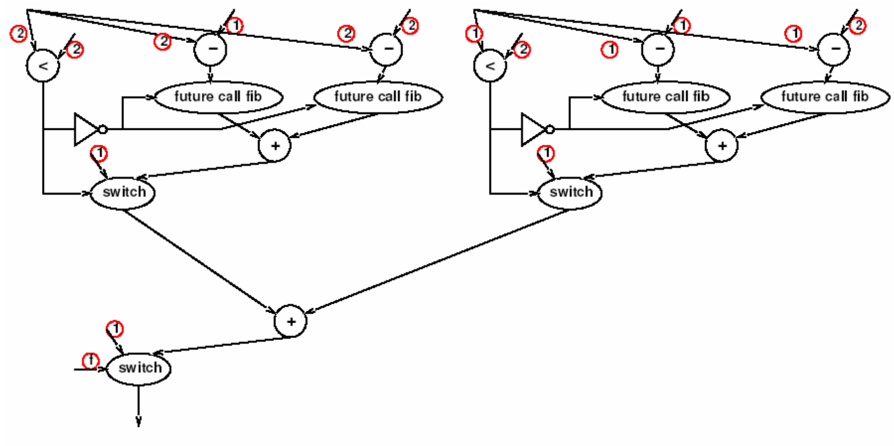

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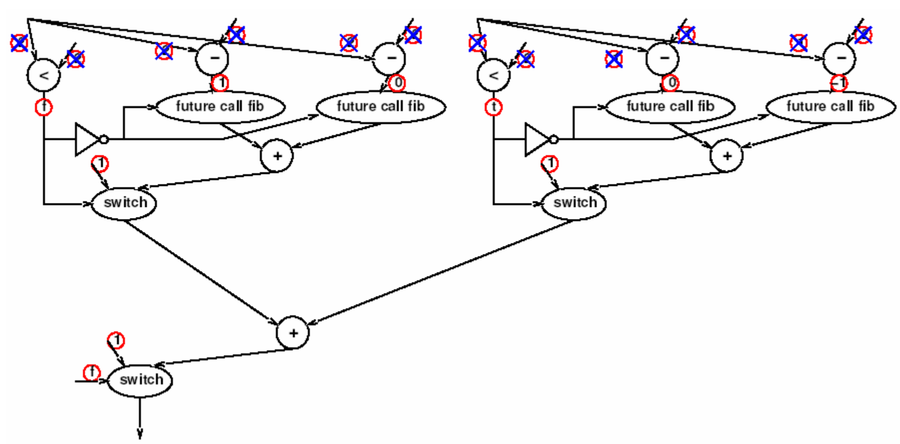

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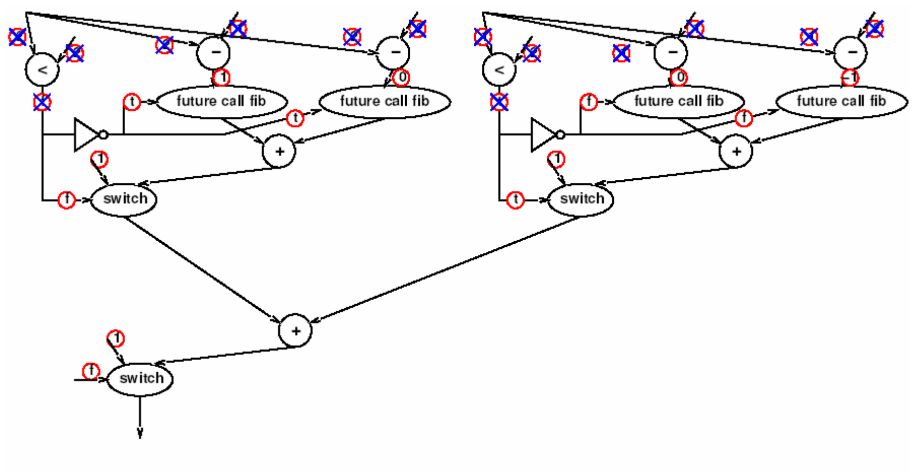

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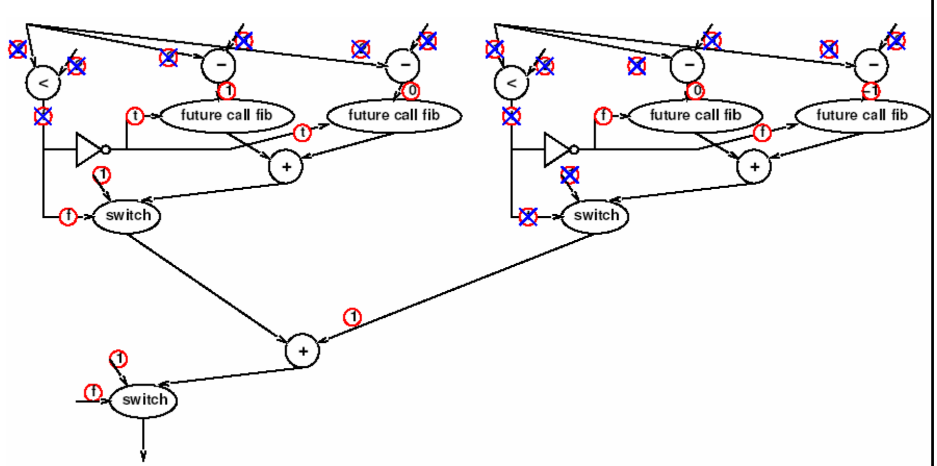

Futures

- Safe with **functional** routines
  - Create dataflow
  - In functional language, can wrap futures around everything
    - Don't need explicit future construct
    - Safe to put it anywhere
      - Anywhere compiler deems worthwhile
- Can introduce non-determinacy with side-effecting routines
  - Not clear when operation completes

Future/Side-Effect hazard

```
(define (decrement! a b)  (set! a (- a b)) a)
(print (* (future (decrement! c d))
          (future (decrement! d e))))
```

```
int decrement (int &a, int &b)
    { *a=*a-*b; return(*a);}
printf("%d %d",
    (future)decrement(&c,&d),
    (future)decrement(&d,&e));
```

Architecture Mechanisms?

- Thread spawn
  - Preferably lightweight
- Full/empty bits
- Pure functional dataflow
  - May exploit common namespace
  - Not need memory coherence in pure functional → values never change

Big Ideas

- Model
- Expose Parallelism
  - Can have model that admits parallelism
  - Can have dynamic (hardware) representation with parallelism exposed
- Tolerate latency with parallelism
- Primitives
  - Thread spawn
  - Synchronization: full/empty