

Microcoded and VLIW Processors

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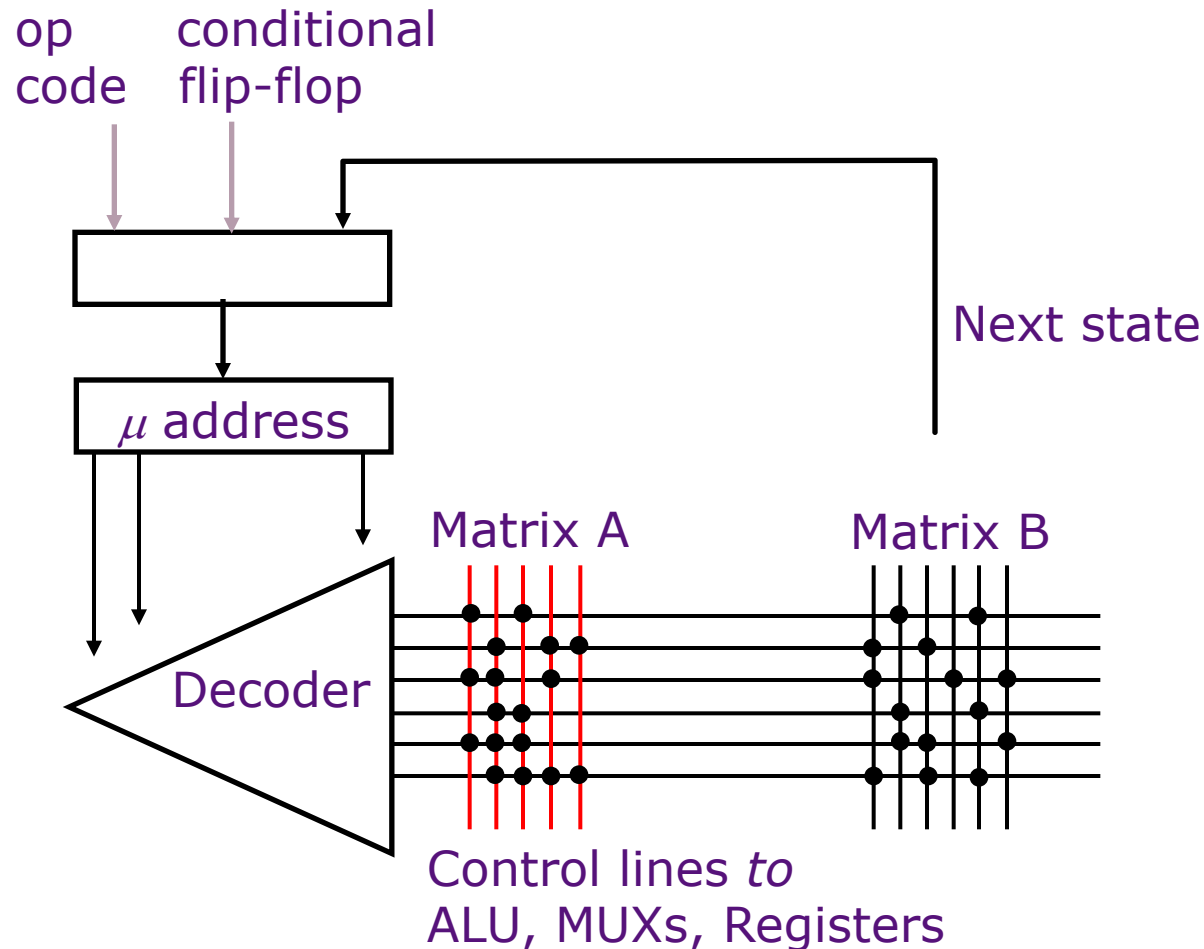
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Hardwired vs Microcoded Processors

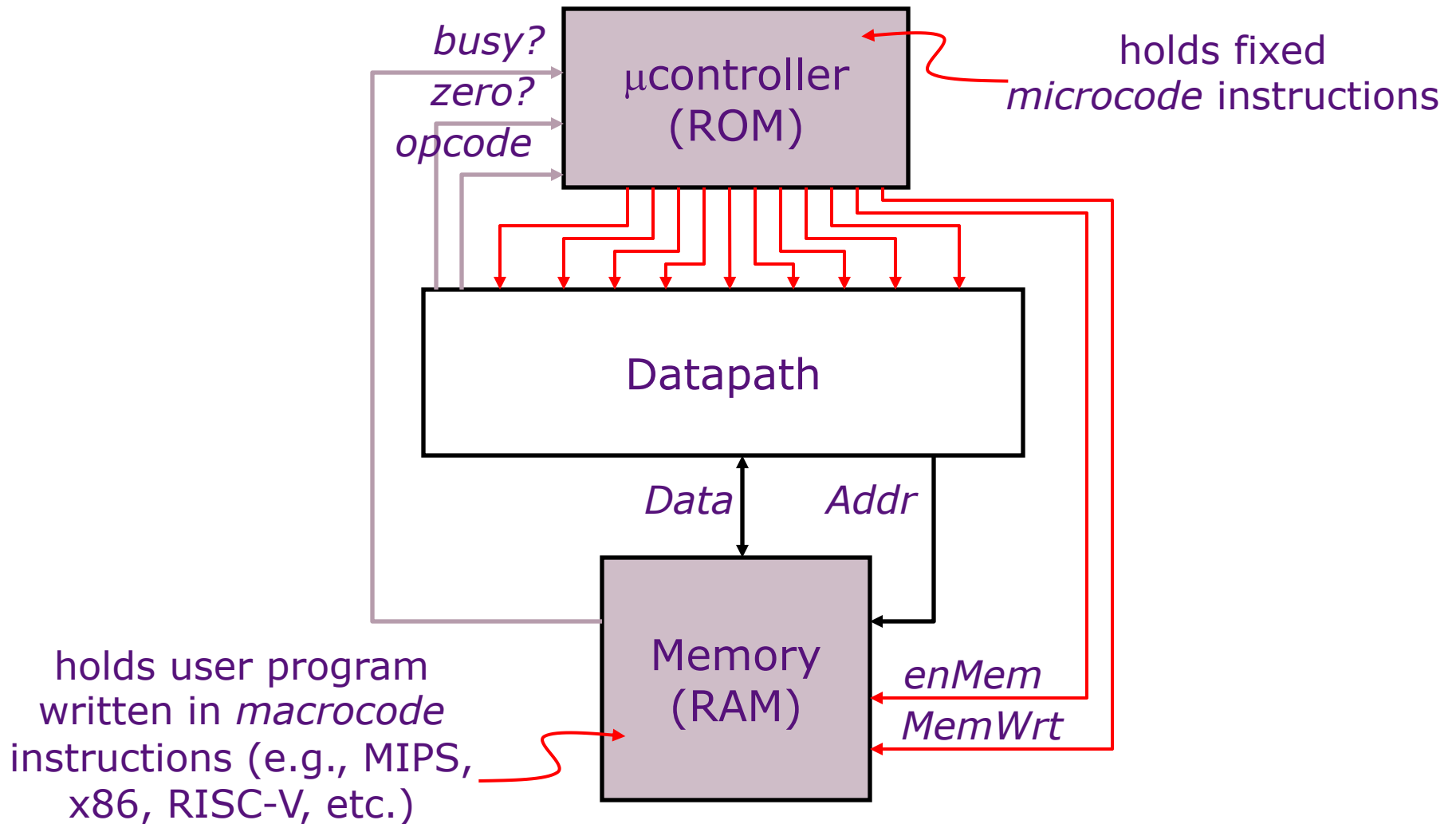
- All processors we have seen so far are *hardwired*: The microarchitecture directly implements all the instructions in the ISA
- *Microcoded processors* add a layer of interpretation: Each ISA instruction is executed as a sequence of simpler *microinstructions*
 - *Simpler implementation*
 - *Lower performance than hardwired ($CPI > 1$)*
- Microcoding common until the 80s, still in use today (e.g., complex x86 instructions are decoded into multiple “micro-ops”)

Microcontrol Unit *[Maurice Wilkes, 1954]*

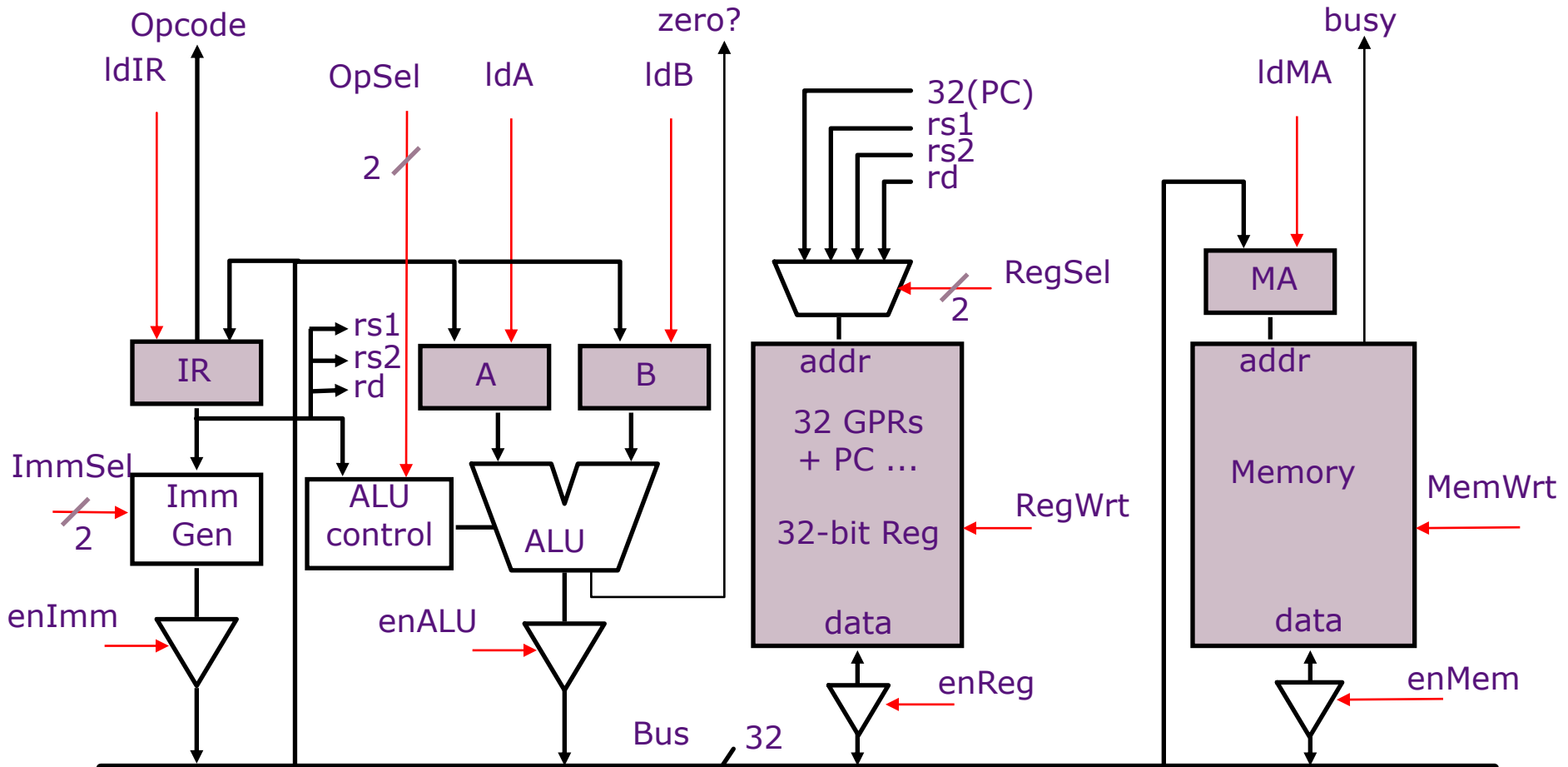
Embed the control logic state table in a read-only memory array



Microcoded Microarchitecture



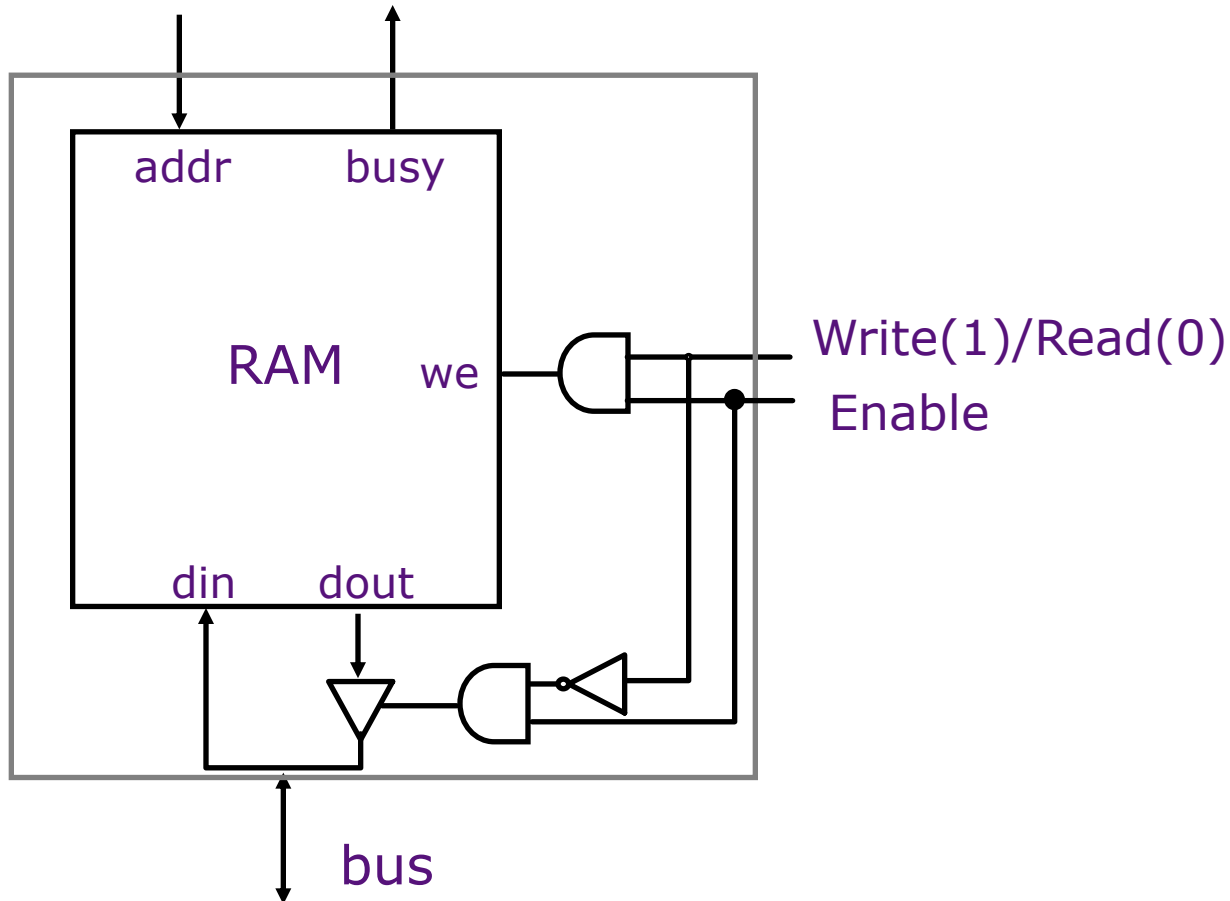
A Bus-based Datapath for RISC-V



Microinstruction: register to register transfer (17 control signals)

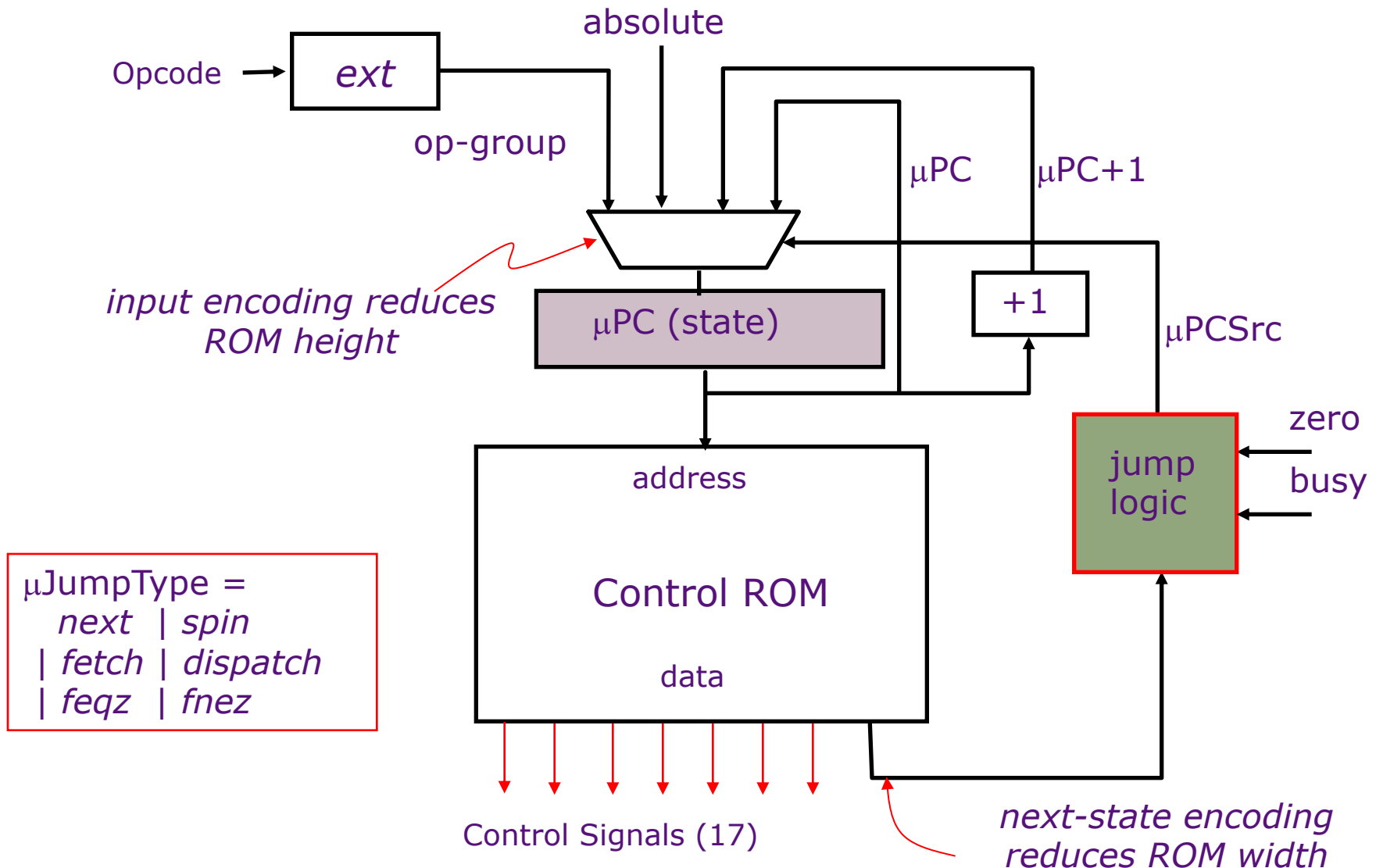
MA \leftarrow PC means RegSel = PC; enReg=yes; IdMA= yes
 B \leftarrow Reg[rs1] means

Memory Module



- Assumption: Memory operates asynchronously and is slow compared to Reg-to-Reg transfers

Microcode Controller



Jump Logic

$\mu\text{PCSrc} = \text{Case } \mu\text{JumpTypes}$

next \Rightarrow $\mu\text{PC}+1$

spin \Rightarrow if (busy) then μPC else $\mu\text{PC}+1$

fetch \Rightarrow absolute

dispatch \Rightarrow op-group

feqz \Rightarrow if (zero) then absolute else $\mu\text{PC}+1$

fnez \Rightarrow if (zero) then $\mu\text{PC}+1$ else absolute

Instruction Execution

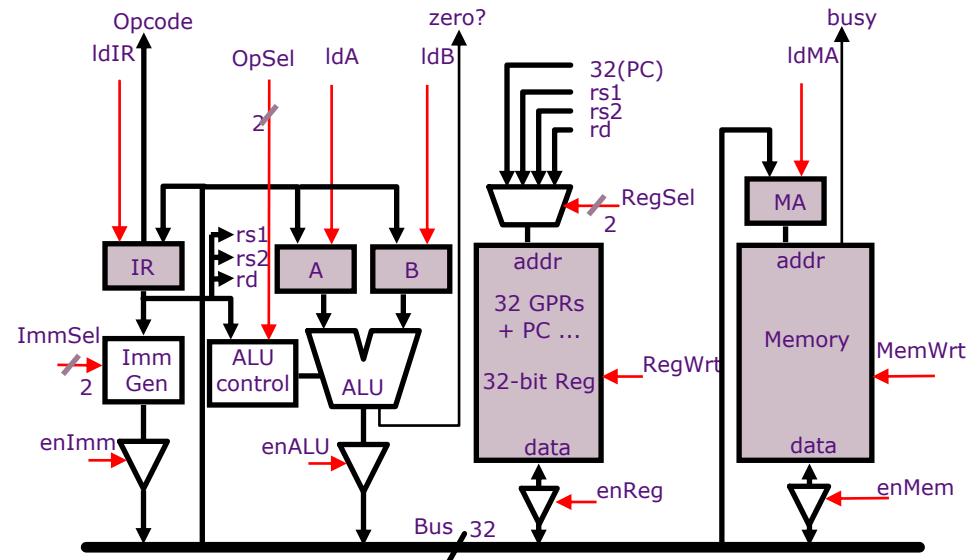
Execution of a RISC-V instruction involves

1. instruction fetch
2. decode and register fetch
3. ALU operation
4. memory operation (optional)
5. write back to register file (optional)
+ the computation of the
next instruction address

Instruction Fetch

State	Control points	next-state
-------	----------------	------------

fetch ₀	MA \leftarrow PC	
fetch ₁	IR \leftarrow Memory	
fetch ₂	A \leftarrow PC	
fetch ₃	PC \leftarrow A + 4	
...		
ALU ₀	A \leftarrow Reg[rs1]	
ALU ₁	B \leftarrow Reg[rs2]	
ALU ₂	Reg[rd] \leftarrow func(A,B)	
ALUi ₀	A \leftarrow Reg[rs]	
ALUi ₁	B \leftarrow sExt(Imm)	
ALUi ₂	Reg[rd] \leftarrow Op(A,B)	



Load & Store

State	Control points	next-state
LW ₀	$A \leftarrow \text{Reg}[\text{rs1}]$	next
LW ₁	$B \leftarrow \text{sExt}(\text{Imm})$	next
LW ₂	$\text{MA} \leftarrow A+B$	next
LW ₃	$\text{Reg}[\text{rd}] \leftarrow \text{Memory}$	spin
LW ₄		fetch
SW ₀	$A \leftarrow \text{Reg}[\text{rs1}]$	next
SW ₁	$B \leftarrow \text{sExt}(\text{Imm})$	next
SW ₂	$\text{MA} \leftarrow A+B$	next
SW ₃	$\text{Memory} \leftarrow \text{Reg}[\text{rs2}]$	spin
SW ₄		fetch

Branches

State	Control points	next-state
BEQ ₀	$A \leftarrow \text{Reg}[\text{rs1}]$	next
BEQ ₁	$B \leftarrow \text{Reg}[\text{rs2}]$	next
BEQ ₂	$A \leftarrow A - B$	next
BEQ ₃		fnez
BEQ ₄	$A \leftarrow \text{PC}$	next
BEQ ₅	$B \leftarrow \text{sExt}(\text{Imm} \ll 1)$	next
BEQ ₆	$\text{PC} \leftarrow A + B$	fetch
BNE ₀	$A \leftarrow \text{Reg}[\text{rs1}]$	next
BNE ₁	$B \leftarrow \text{Reg}[\text{rs2}]$	next
BNE ₂	$A \leftarrow A - B$	next
BNE ₃		feqz
BNE ₄	$A \leftarrow \text{PC}$	next
BNE ₅	$B \leftarrow \text{sExt}(\text{Imm} \ll 1)$	next
BNE ₆	$\text{PC} \leftarrow A + B$	fetch

Branches

State	Control points	next-state
BLT ₀	$A \leftarrow \text{Reg}[\text{rs1}]$	next
BLT ₁	$B \leftarrow \text{Reg}[\text{rs2}]$	next
BLT ₂	$A \leftarrow \text{slt}(A, B)$	next
BLT ₃		feqz
BLT ₄	$A \leftarrow \text{PC}$	next
BLT ₅	$B \leftarrow \text{sExt}(\text{Imm} \ll 1)$	next
BLT ₆	$\text{PC} \leftarrow A + B$	fetch

Similar sequences for BGE, BLTU, BGEU

Jumps

State	Control points	next-state
JAL ₀	$A \leftarrow PC$	next
JAL ₁	$Reg[rd] \leftarrow A$	next
JAL ₂	$B \leftarrow IR$	next
JAL ₃	$PC \leftarrow \text{JumpTarg}(A,B)$	fetch
JALR ₀	$A \leftarrow Reg[rs1]$	next
JALR ₁	$B \leftarrow PC$	next
JALR ₂	$Reg[rd] \leftarrow B$	next
JALR ₃	$B \leftarrow IR$	next
JALR ₄	$PC \leftarrow \text{JumpTarg}(A,B)$	fetch

VAX 11-780 Microcode (1978)

```

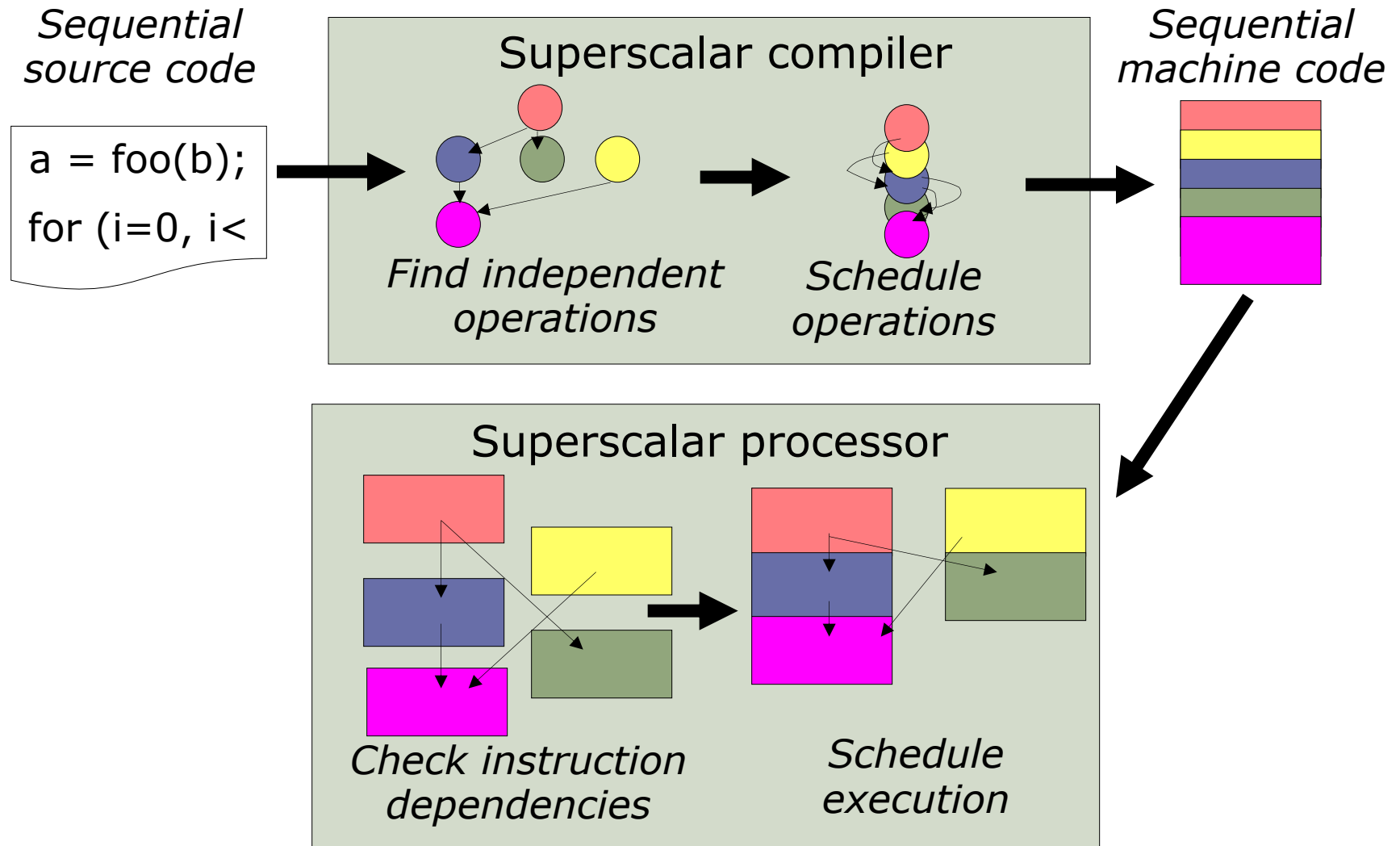
●  P1WFUD,1 [600,1205] MICRO2 1F(12) 26-May-81 14:58:11 VAX11/780 Microcode : PCS 01, FPLA 0D, WCS122 Page 771
●  CALL2 ,MIC [600,1205] Procedure call : CALLG, CALLS

●                                     ;29744 ;HERE FOR CALLG OR CALLS, AFTER PROBING THE EXTENT OF THE STACK
●                                     ;29745
●                                     ;29746 =0 ;-----;CALL SITE FOR MPUSH
● 6557K 0 U 11F4, 0811,2035,0180,F910,0000,0CD8 ;29747 CALL,7: D_Q,AND,RC[T2], ;STRIP MASK TO BITS 11-0
●                                     ;29748 CALL,J/MPUSH ;PUSH REGISTERS
●                                     ;29749
●                                     ;29750 ;-----;RETURN FROM MPUSH
● 6557K 7763K U 11F5, 0000,003C,0180,3270,0000,134A ;29751 CACHE_D[LONG], ;PUSH PC
●                                     ;29752 LAB_R[SP] ; BY SP
●                                     ;29753
● 6856K 0 U 134A, 0018,0000,0180,FAF0,0200,134C ;29754 ;-----;
●                                     ;29755 CALL,8: R[SP]&VA_LA=K[,8] ;UPDATE SP FOR PUSH OF PC &
●                                     ;29756
● 6856K 0 U 134C, 0800,003C,0180,FA68,0000,11F8 ;29757 ;-----;
●                                     ;29758 D_R[FP] ;READY TO PUSH FRAME POINTER
●                                     ;29759
●                                     ;29760 =0 ;-----;CALL SITE FOR PSHSP
●                                     ;29761 CACHE_D[LONG], ;STORE FP,
●                                     ;29762 LAB_R[SP], ; GET SP AGAIN
● 6856K 21M U 11F8, 0000,003D,6D80,3270,0084,6CD9 ;29763 SC_K[.FFF0], ;=16 TO SC
●                                     ;29764 CALL,J/PSHSP
●                                     ;29765
●                                     ;29766 ;-----;
● 6856K 0 U 11F9, 0800,003C,3DF0,2E60,0000,134D ;29767 D_R[AP], ;READY TO PUSH AP
●                                     ;29768 Q_ID[PSL] ; AND GET PSW FOR COMBINATIO
●                                     ;29769
●                                     ;29770 ;-----;
● 6856K 21M U 134D, 0019,2024,8DC0,3270,0000,134E ;29771 CACHE_D[LONG], ;STORE OLD AP
●                                     ;29772 Q_Q,ANDNOT,K[,1F], ;CLEAR PSW<T,N,Z,V,C>
●                                     ;29773 LAB_R[SP] ;GET SP INTO LATCHES AGAIN
●                                     ;29774
● 6856K 0 U 134E, 2010,0038,0180,F909,4200,1350 ;29775 ;-----;
●                                     ;29776 PC&VA_RC[T1], FLUSH,IB ; LOAD NEW PC AND CLEAR OUT
●                                     ;29777
●                                     ;29778 ;-----;
●                                     ;29779 D_DAL.SC, ;PSW TO D<31:16>
●                                     ;29780 Q_RC[T2], ;RECOVER MASK
● 6856K 0 U 1350, 0D10,0038,0DC0,6114,0084,9351 ;29781 SC=SC+K[,3], ;PUT -13 IN SC
●                                     ;29782 LOAD,IB, PC_PC+1 ;START FETCHING SUBROUTINE I
●                                     ;29783
●                                     ;29784 ;-----;
●                                     ;29785 D_DAL.SC, ;MASK AND PSW IN D<31:03>
● 6856K 0 U 1351, 0D10,0038,F5C0,F920,0084,9352 ;29786 Q_PC[T4], ;GET LOW BITS OF OLD SP TO Q<1:0>
●                                     ;29787 SC=SC+K[,A] ;PUT -3 IN SC
●                                     ;29788

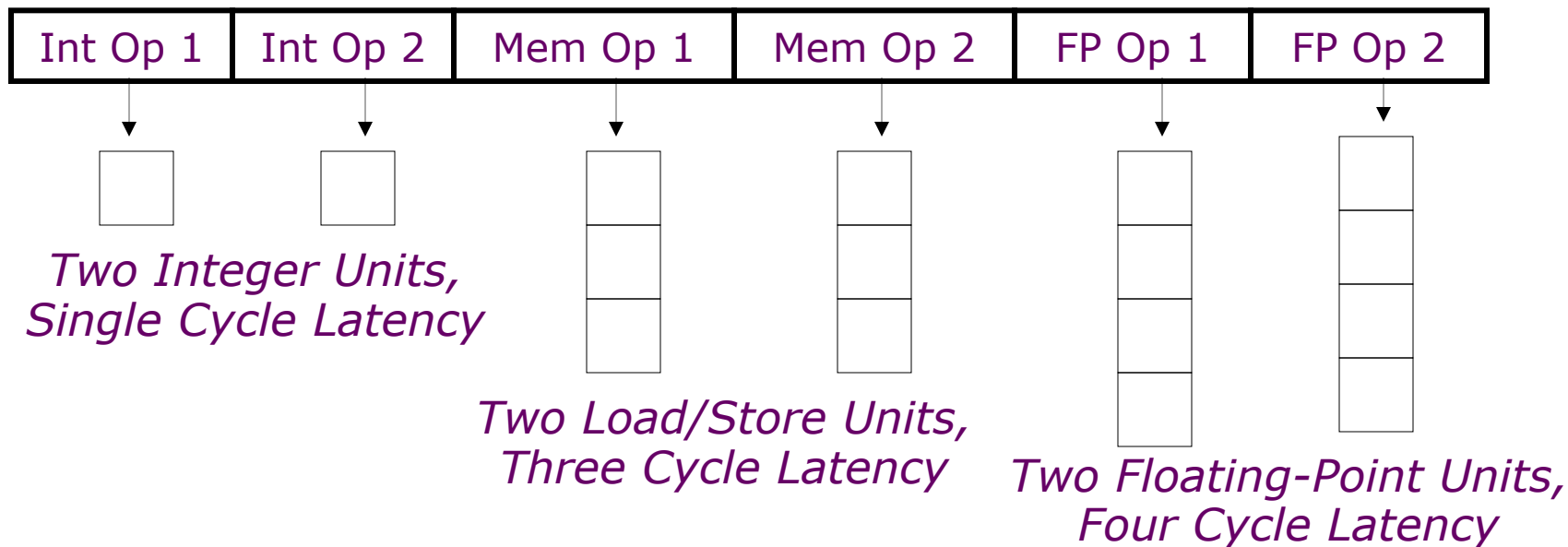
```

Very Long Instruction Word (VLIW) Processors

Sequential ISA Bottleneck



VLIW: Very Long Instruction Word



- Multiple operations packed into one instruction
- Each operation slot is for a fixed function
- Constant operation latencies are specified

VLIW Design Principles

The architecture:

- Allows operation parallelism within an instruction
 - No cross-operation RAW check
- Provides deterministic latency for all operations
 - Latency measured in 'instructions'
 - No data use allowed before specified latency with no data interlocks

The compiler:

- Schedules (reorders) to maximize parallel execution
- Guarantees intra-instruction parallelism
- Schedules to avoid data hazards (no interlocks)
 - Typically separates operations with explicit NOPs

Early VLIW Machines

- FPS AP120B (1976)
 - scientific attached array processor
 - first commercial wide instruction machine
 - hand-coded vector math libraries using software pipelining and loop unrolling
- Multiflow Trace (1987)
 - commercialization of ideas from Fisher's Yale group including "trace scheduling"
 - available in configurations with 7, 14, or 28 operations/instruction
 - 28 operations packed into a 1024-bit instruction word
- Cydrome Cydra-5 (1987)
 - 7 operations encoded in 256-bit instruction word
 - rotating register file

Loop Execution

```
for (i=0; i<N; i++)  
    B[i] = A[i] + C;
```

Compile

```
loop: fld f1, 0(x1)  
      add x1, 8  
      fadd.d f2, f0, f1  
      fsd f2, 0(x2)  
      add x2, 8  
      bne x1, x3, loop
```

Schedule

loop:

Int1	Int 2	M1	M2	FP+	FPx
add x1		fld			
				fadd.d	
add x2 bne		fsd			

How many FP ops/cycle?

Loop Unrolling

```
for (i=0; i<N; i++)  
    B[i] = A[i] + C;
```

Unroll inner loop to
perform 4 iterations
at once

```
for (i=0; i<N; i+=4)  
{  
    B[i]    = A[i] + C;  
    B[i+1] = A[i+1] + C;  
    B[i+2] = A[i+2] + C;  
    B[i+3] = A[i+3] + C;  
}
```

Is this code always correct?

Scheduling Loop Unrolled Code

Unroll 4 ways

```
loop: fld f1, 0(x1)
      fld f2, 8(x1)
      fld f3, 16(x1)
      fld f4, 24(x1)
      add x1, 32
      fadd.d f5, f0, f1
      fadd.d f6, f0, f2
      fadd.d f7, f0, f3
      fadd.d f8, f0, f4
      fsd f5, 0(x2)
      fsd f6, 8(x2)
      fsd f7, 16(x2)
      fsd f8, 24(x2)
      add x2, 32
      bne x1, x3, loop
```

loop:

Schedule

Int1 Int 2 M1 M2 FP+ FPx

		fld f1			
		fld f2			
		fld f3			
add x1		fld f4		fadd.d f5	
				fadd.d f6	
				fadd.d f7	
				fadd.d f8	
		fsd f5			
		fsd f6			
		fsd f7			
add x2	bne	fsd f8			

How many FLOPS/cycle?

Software Pipelining

Unroll 4 ways first

```

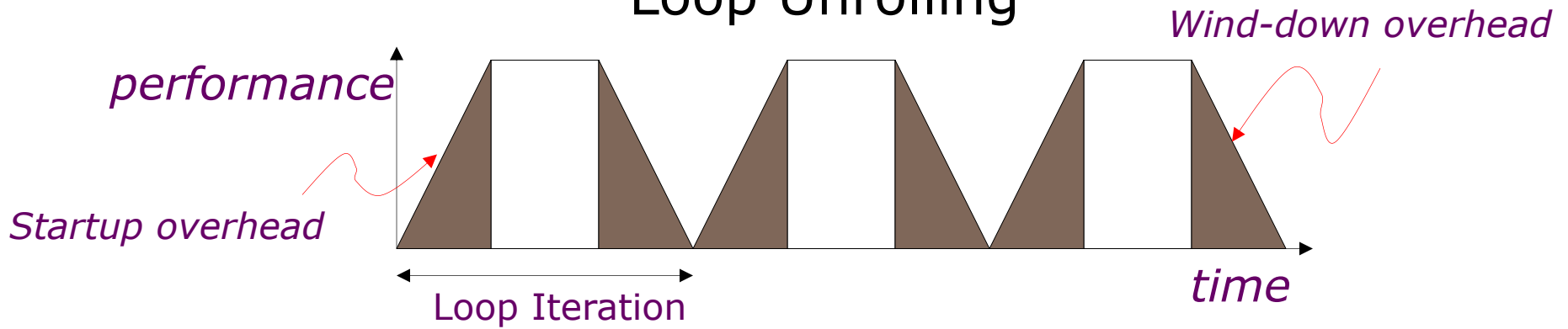
loop: fld f1, 0(x1)
      fld f2, 8(x1)
      fld f3, 16(x1)
      fld f4, 24(x1)
      add x1, 32
      fadd.d f5, f0, f1
      fadd.d f6, f0, f2
      fadd.d f7, f0, f3
      fadd.d f8, f0, f4
      fsd f5, 0(x2)
      fsd f6, 8(x2)
      fsd f7, 16(x2)
      fsd f8, -8(x2)
      add x2, 32
      bne x1, x3, loop
    
```

	Int1	Int 2	M1	M2	FP+	FPx
prolog			fld f1			
			fld f2			
			fld f3			
	add x1		fld f4			
			fld f1		fadd.d f5	
			fld f2		fadd.d f6	
			fld f3		fadd.d f7	
	add x1		fld f4		fadd.d f8	
iterate			fld f1	fsd f5	fadd.d f5	
			fld f2	fsd f6	fadd.d f6	
		add x2	fld f3	fsd f7	fadd.d f7	
	add x1	bne	fld f4	fsd f8	fadd.d f8	
				fsd f5	fadd.d f5	
				fsd f6	fadd.d f6	
		add x2		fsd f7	fadd.d f7	
		bne		fsd f8	fadd.d f8	
epilog				fsd f5		

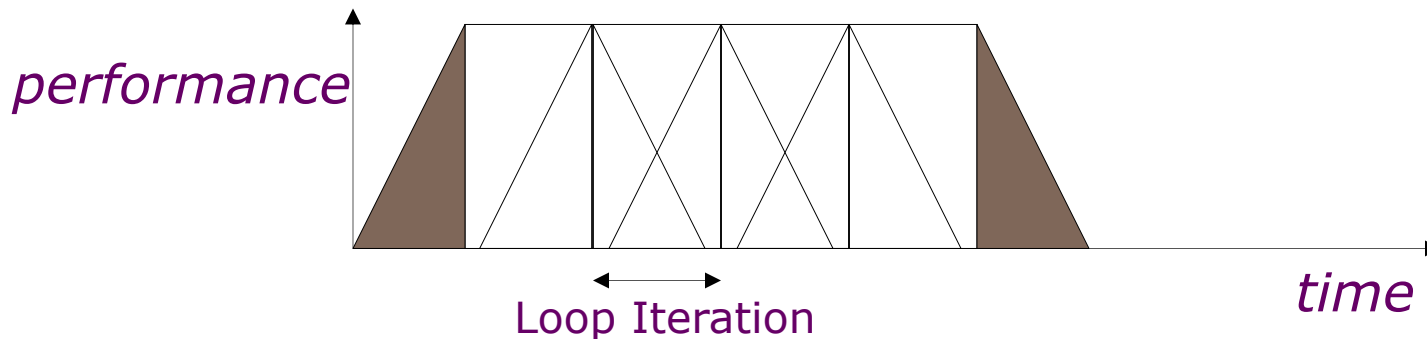
How many FLOPS/cycle?

Software Pipelining vs. Unrolling

Loop Unrolling

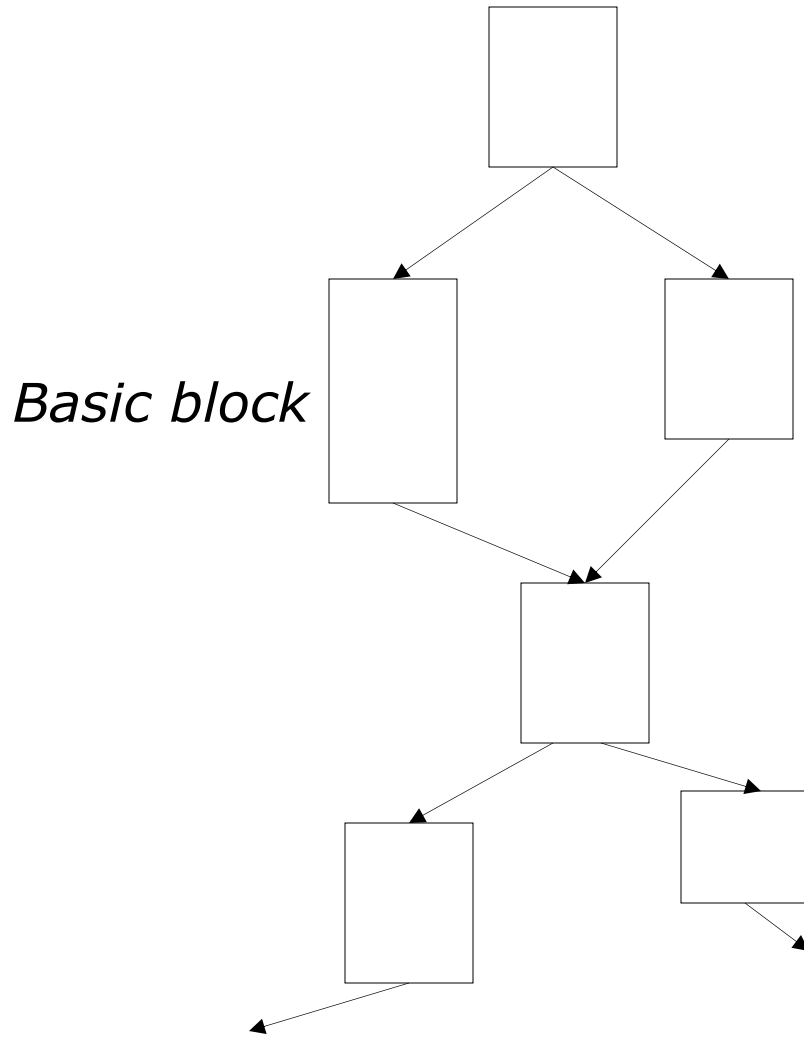


Software Pipelining



Software pipelining pays startup/wind-down costs only once per loop, not once per iteration

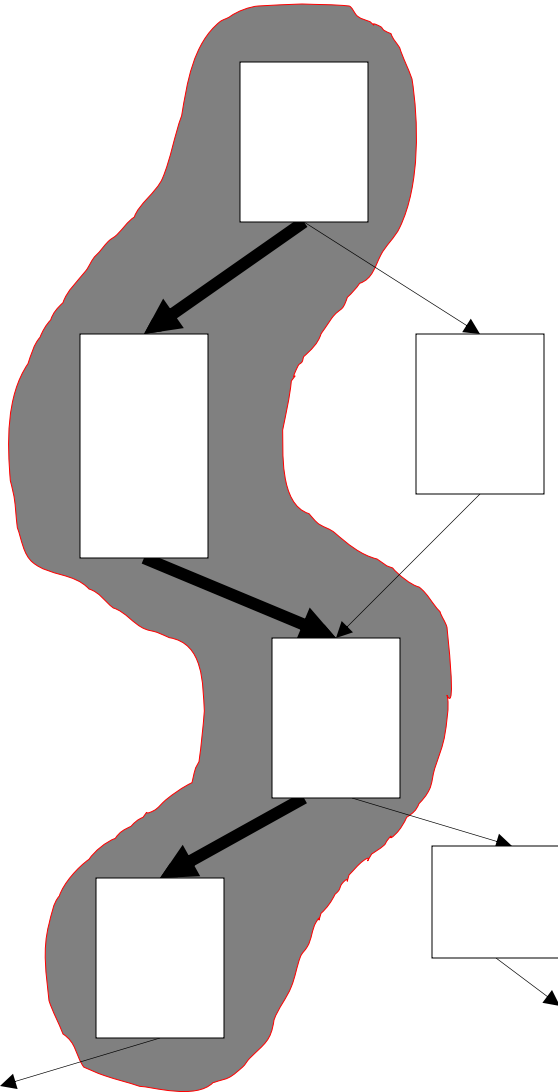
What if there are no loops?



- Branches limit basic block size in control-flow intensive irregular code
- Difficult to find ILP in individual basic blocks

Trace Scheduling

[Fisher, Ellis]



- Pick string of basic blocks, a trace, that represents most frequent branch path
- Schedule whole “trace” at once
- Add fixup code to cope with branches jumping out of trace

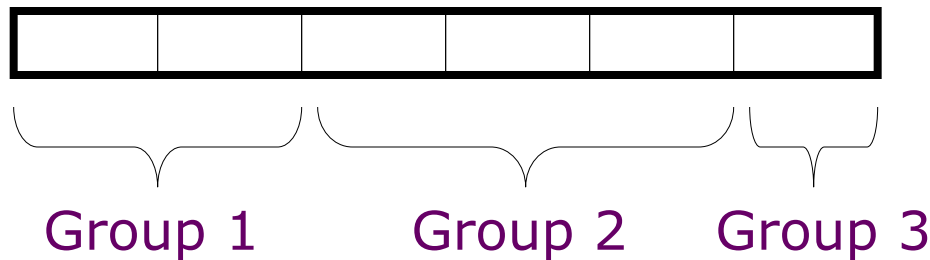
How do we know which trace to pick?

Problems with “Classic” VLIW

- Knowing branch probabilities
 - Profiling requires an significant extra step in build process
- Scheduling for statically unpredictable branches
 - Optimal schedule varies with branch path
- Object code size
 - Instruction padding wastes instruction memory/cache
 - Loop unrolling/software pipelining replicates code
- Scheduling memory operations
 - Caches and/or memory bank conflicts impose statically unpredictable variability
 - Uncertainty about addresses limit code reordering
- Object-code compatibility
 - Have to recompile all code for every machine, even for two machines in same generation

VLIW Instruction Encoding

- Schemes to reduce effect of unused fields
 - Compressed format in memory, expand on I-cache refill
 - used in Multiflow Trace
 - introduces instruction addressing challenge
 - Provide a single-op VLIW instruction
 - Cydra-5 UniOp instructions
 - Mark parallel groups
 - used in TMS320C6x DSPs, Intel IA-64



Cydra-5: Memory Latency Register (MLR)

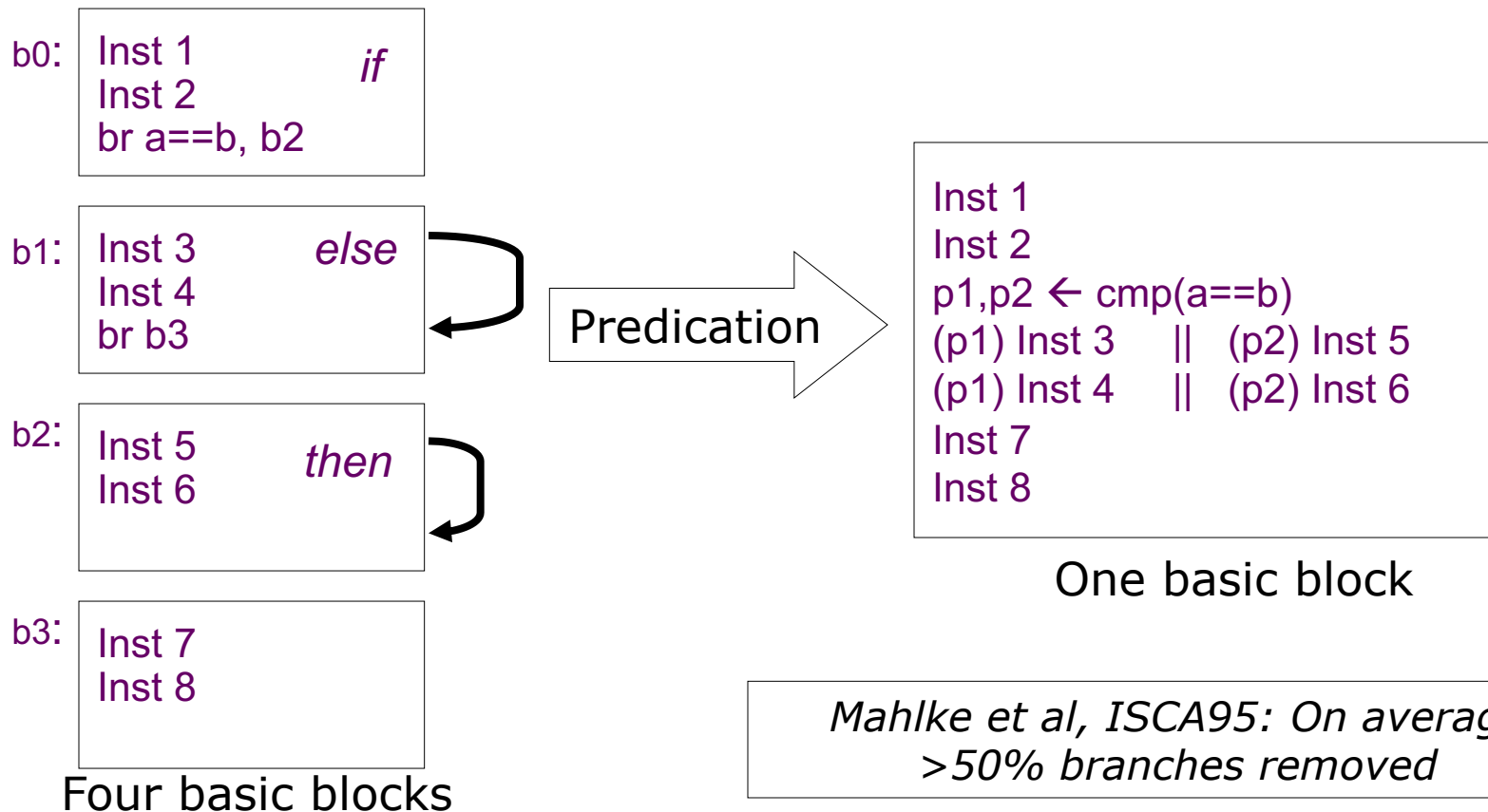
- Problem: Loads have variable latency
- Solution: Let software choose desired memory latency
- Compiler schedules code for maximum load-use distance
- Software sets MLR to latency that matches code schedule
- Hardware ensures that loads take exactly MLR cycles to return values into processor pipeline
 - Hardware buffers loads that return early
 - Hardware stalls processor if loads return late

IA-64 Predicated Execution

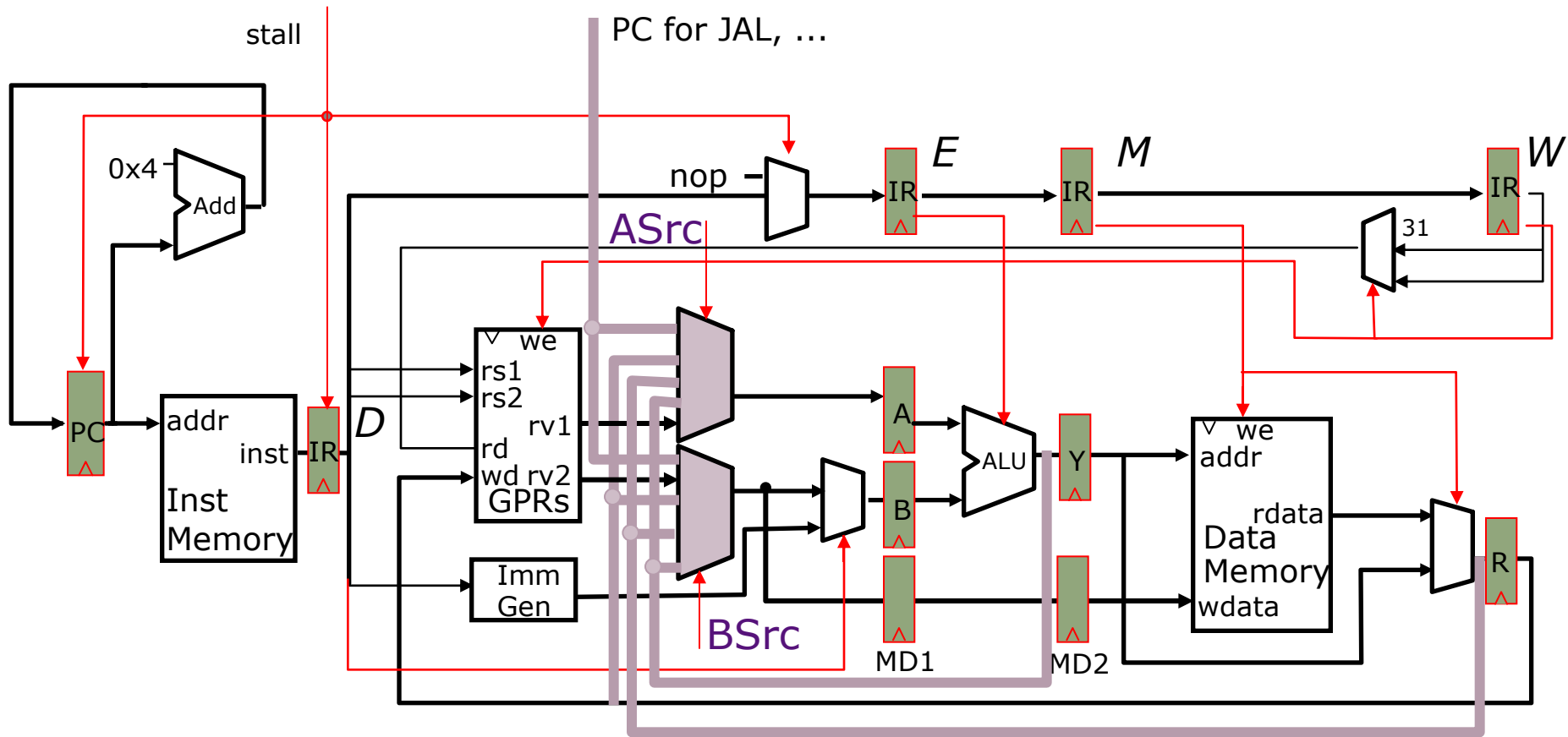
Problem: Mispredicted branches limit ILP

Solution: Eliminate hard-to-predict branches with predicated execution

- Almost all IA-64 instructions can be executed conditionally under predicate
- Instruction becomes NOP if predicate register false



Fully Bypassed Datapath

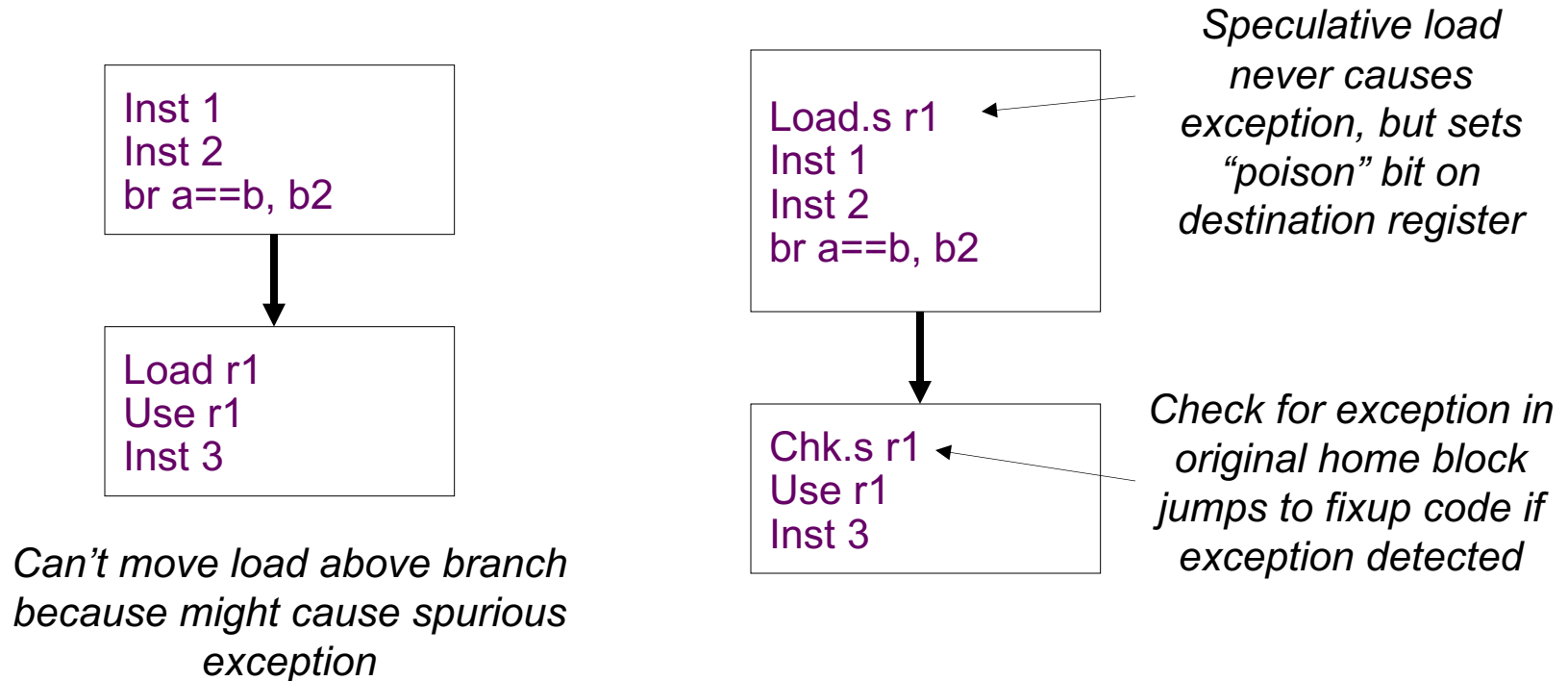


Where does predication fit in?

IA-64 Speculative Execution

Problem: Branches restrict compiler code motion

Solution: Speculative operations that don't cause exceptions

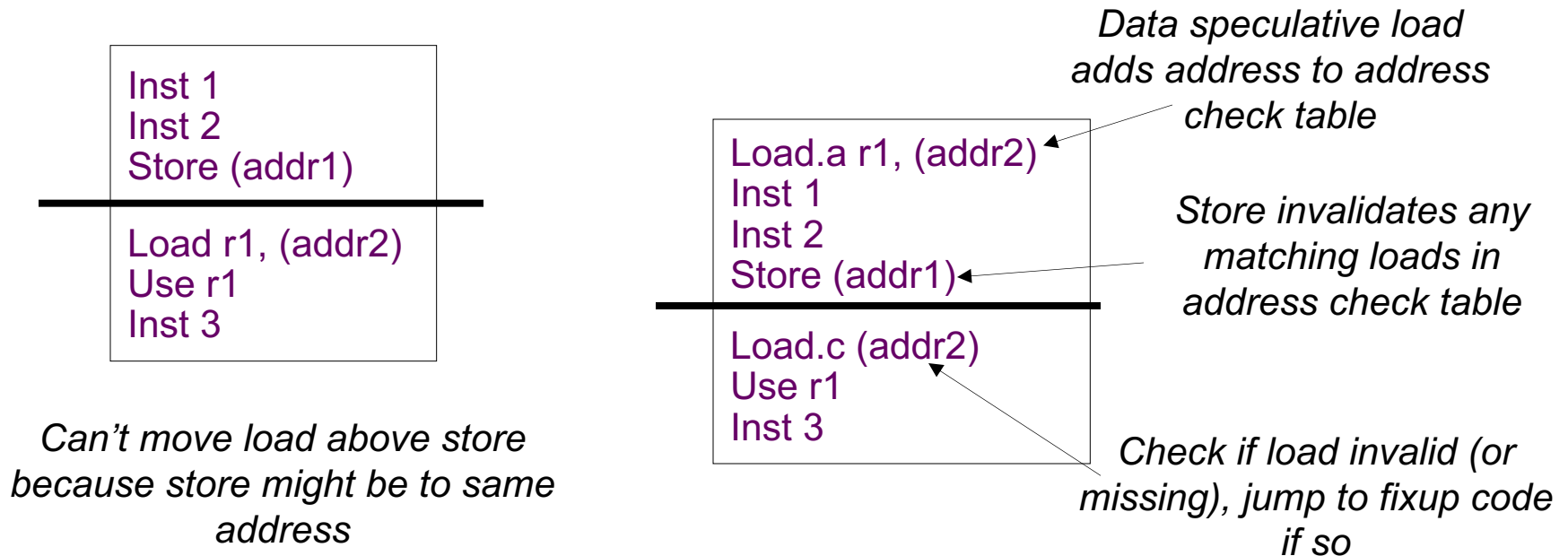


Particularly useful for scheduling long latency loads early

IA-64 Data Speculation

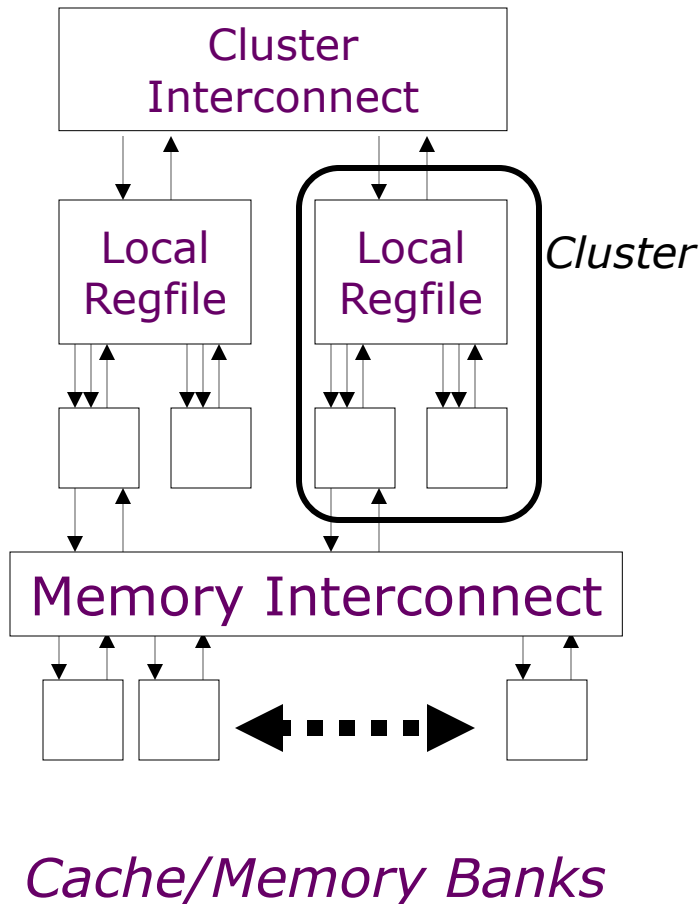
Problem: Possible memory hazards limit code scheduling

Solution: Instruction-based speculation with hardware monitor to check for pointer hazards



Requires associative hardware in address check table

Clustered VLIW



- Divide machine into clusters of local register files and local functional units
- Lower bandwidth/higher latency interconnect between clusters
- Software responsible for mapping computations to minimize communication overhead
- Common in commercial embedded processors, examples include TI C6x series DSPs, and HP Lx processor
- Exists in some superscalar processors, e.g., Alpha 21264

Limits of Static Scheduling

- Unpredictable branches
- Unpredictable memory behavior (cache misses and dependencies)
- Code size explosion
- Compiler complexity

Question:

How applicable are VLIW-inspired techniques to traditional RISC/CISC processor architectures?

Thank you!

Next Lecture: Reliability

