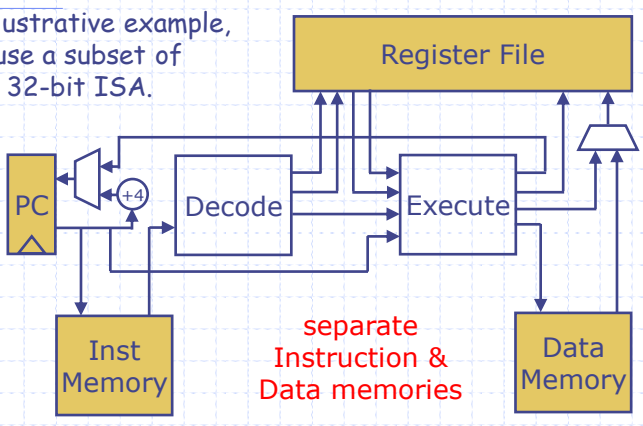
Non-Pipelined Processors

Arvind
Computer Science & Artificial Intelligence Lab.
Massachusetts Institute of Technology

Single-Cycle RISC Processor

As an illustrative example, we will use a subset of RISC-V 32-bit ISA.



Datapath and control are derived automatically from a high-level rule-based description

Single-Cycle Implementation

code structure

```
module mkProc(Proc);
  Reg#(Addr)  pc <- mkRegU;
  RFile       rf <- mkRFile;
  IMemory     iMem <- mkIMemory;
  DMemory     dMem <- mkDMemory;

  rule doProc;
    let inst = iMem.req(pc);
    let dInst = decode(inst);
    let rVal1 = rf.rd1(dInst.rSrc1);
    let rVal2 = rf.rd2(dInst.rSrc2);
    let eInst = exec(dInst, rVal1, rVal2, pc);

    update rf, pc and dMem
```

to be explained later

instantiate the state

extracts fields needed for execution

produces values needed to update the processor state

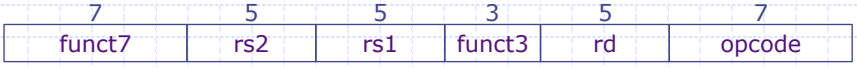
RISC-V Register States

- 32 general purpose registers (GPR)
  - x0, x1, …, x31
  - 32-bit wide integer registers
  - x0 is hard-wired to zero
- Program counter (PC)
  - 32-bit wide
- CSR (Control and Status Registers)
  - cycle
  - instret
  - mhartid
  - mtohost
  - …

will be implemented in labs as needed

Computational Instructions

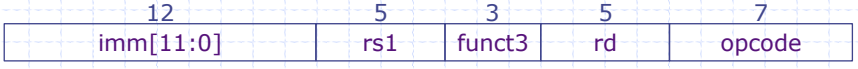
- Register-Register instructions (R-type)



  - opcode=OP: rd ← rs1 (funct3, funct7) rs2
  - funct3 = SLT/SLTU/AND/OR/XOR/SLL
  - funct3= ADD
    - funct7 = 0000000: rs1 + rs2
    - funct7 = 0100000: rs1 – rs2
  - funct3 = SRL
    - funct7 = 0000000: logical shift right
    - funct7 = 0100000: arithmetic shift right

Computational Instructions *cont*

- Register-immediate instructions (I-type)

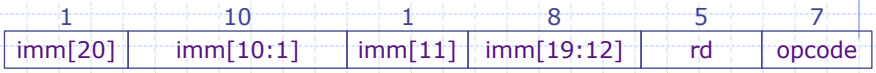


  - opcode = OP-IMM: rd ← rs1 (funct3) I-imm
  - I-imm = signExtend(inst[31:20])
  - funct3 = ADDI/SLTI/SLTIU/ANDI/ORI/XORI

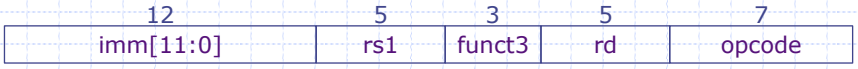
- A slight variant in coding for shift instructions - SLLI / SRLI / SRAI
  - rd ← rs1 (funct3, inst[30]) I-imm[4:0]

Control Instructions

- Unconditional jump and link (UJ-type)



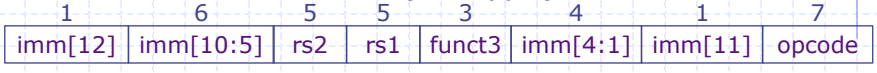
  - opcode = JAL: rd ← pc + 4; pc ← pc + J-imm
  - J-imm = signExtend({inst[31], inst[19:12], inst[20], inst[30:21], 1'b0})
  - Jump ±1MB range
- Unconditional jump via register and link (I-type)



  - opcode = JALR: rd ← pc + 4; pc ← (rs1 + I-imm) & ~0x01
  - I-imm = signExtend(inst[31:20])

Control Instructions *cont.*

- Conditional branches (SB-type)



  - opcode = BRANCH: pc ← compare(funct3, rs1, rs2) ? pc + B-imm : pc + 4
  - B-imm = signExtend({inst[31], inst[7], inst[30:25], inst[11:8], 1'b0})
  - Jump ±4KB range
  - funct3 = BEQ/BNE/BLT/BLTU/BGE/BGEU

1'b0 means it's half-word aligned. This is because RISC V allows 16-bit compressed format of instructions

Load & Store Instructions

- Load (I-type)

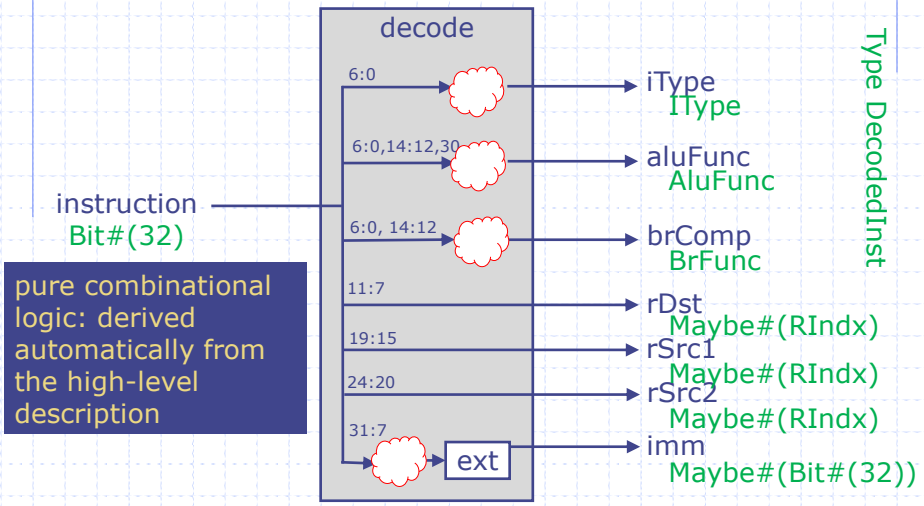
12	5	3	5	7
imm[11:0]	rs1	funct3	rd	opcode

  - opcode = LOAD: rd ← mem[rs1 + I-imm]
  - I-imm = signExtend(inst[31:20])
  - funct3 = LW/LB/LBU/LH/LHU
- Store (S-type)

7	5	5	3	5	7
imm[11:5]	rs2	rs1	funct3	imm[4:0]	opcode

  - opcode = STORE: mem[rs1 + S-imm] ← rs2
  - S-imm = signExtend({inst[31:25], inst[11:7]})
  - funct3 = SW/SB/SH

Decoding Instructions:
extract fields needed for execution



pure combinational logic: derived automatically from the high-level description

Decoded Instruction Type

```
typedef struct {
  IType             iType;
  AluFunc           aluFunc;
  BrFunc            brFunc;
  Maybe#(RIndx)     dst;
  Maybe#(RIndx)     src1;
  Maybe#(RIndx)     src2;
  Maybe#(Data)      imm;
} DecodedInst deriving(Bits, Eq);

typedef enum {Unsupported, Alu, Ld, St, J, Jr, Br, Auipc}
IType deriving(Bits, Eq);
typedef enum {Add, Sub, And, Or, Xor, Slt, Sltu, Sll,
Sra, Srl} AluFunc deriving(Bits, Eq);
typedef enum {Eq, Neq, Lt, Ltu, Ge, Geu, AT, NT} BrFunc
deriving(Bits, Eq);
```

Destination register 0 behaves like an Invalid destination

Instruction groups with similar executions paths

Internal names for various opcode and funct3 patterns

```
// opcode
Bit#(7) opOpImm  = 7'b0010011; // OP-IMM
Bit#(7) opOp     = 7'b0110011; // OP
Bit#(7) opLui    = 7'b0110111; // LUI
Bit#(7) opAuipc  = 7'b0010111; // AUIPC ...
Bit#(7) opJal    = 7'b1101111; // JAL
Bit#(7) opJalr   = 7'b1100111; // JALR
Bit#(7) opBranch = 7'b1100011; // BRANCH
Bit#(7) opLoad   = 7'b0000011; // LOAD
Bit#(7) opStore  = 7'b0100011; // STORE
// funct3
Bit#(3) fnADD    = 3'b000; // ADD
Bit#(3) fnSLL    = 3'b001; // SLL
Bit#(3) fnSLT    = 3'b010; // SLT .....
```

Values are specified in the RISC-V ISA

Decode Function

```
function DecodedInst decode(Bit#(32) inst);
   DecodedInst dInst = ?;
   let opcode = inst[  6 :  0 ];
   let rd     = inst[ 11 :  7 ];
   let funct3 = inst[ 14 : 12 ];
   let rs1    = inst[ 19 : 15 ];
   let rs2    = inst[ 24 : 20 ];
   let aluSel = inst[ 30 ]; // Add/Sub, Srl/Sra
   Bit#(32)immI=…; Bit#(32)immS=…; Bit#(32)immB=…;
   Bit#(32)immU=…; Bit#(32)immJ=…; // I/S/B/U/J-imm
   case (opcode)
     opOp
     ...
   endcase
   return dInst;
endfunction
```

initially undefined

Decoding Instructions: Computational Instructions

```
opOp: begin
    dInst.iType = Alu;
    dInst.aluFunc = case (funct3)
        fnAND:  And;
        fnSLTU: Sltu;
        …
        fnADD:  Add;
        fnSR:   aluSel == 0 ? Srl : Sra;
    endcase;
    dInst.brFunc = NT;
    dInst.dst = Valid rd;
    dInst.src1 = Valid rs1;
    dInst.src2 = Invalid;
    dInst.imm =  Valid ImmI;
end
```

Decoding instructions with immediate operand (i.e. opcode = OP-IMM) is similar

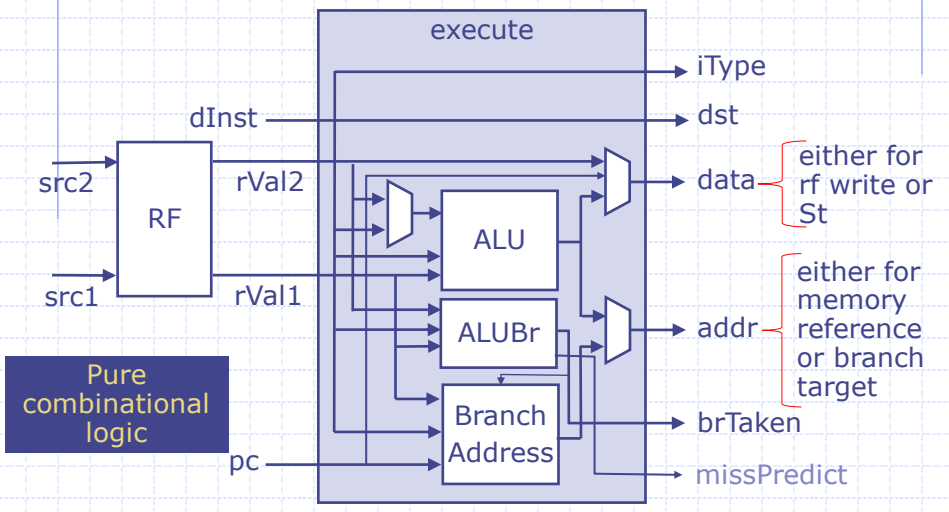
Decoding Instructions: Conditional Branch

```
opBranch: begin
    Maybe#(BrFunc) brF =
        case(funct3)
        fnBEQ:  Valid Eq;
        …
        fnBGEU: Valid Geu;
        default: Invalid;
    endcase;
    dInst.iType = isValid(brF) ? Br : Unsupported;
    dInst.aluFunc = ?;
    dInst.brFunc = fromMaybe(?, brF);
    dInst.dst = Invalid;
    dInst.src1 = Valid rs1;
    dInst.src2 = Valid rs2;
    dInst.imm = Valid immB;
end
```


Decoding Instructions: Load & Store

```
opLoad: begin // only support LW
    dInst.iType = funct3 == fnLW ? Ld : Unsupported;
    dInst.aluFunc = Add; // calc effective addr
    dInst.brFunc = NT;
    dInst.dst = Valid rd;
    dInst.src1 = Valid rs1;
    dInst.src2 = Invalid;
    dInst.imm = Valid immI;
end
opStore: begin // only support SW
    dInst.iType = funct3 == fnSW ? St : Unsupported;
    dInst.aluFunc = Add; // calc effective addr
    dInst.brFunc = NT;
    dInst.dst = Invalid;
    dInst.src1 = Valid rs1;
    dInst.src2 = Valid rs2;
    dInst.imm = Valid immS;
end
```

Reading Registers and Executing Instructions



Output type of exec function

```
typedef struct {
  IType             iType;
  Maybe#(RIndx)     dst;
  Data              data;
  Addr              addr;
  Bool              mispredict;
  Bool              brTaken;
} ExecInst deriving(Bits, Eq);
```

Execute Function

```
function ExecInst exec(DecodedInst dInst, Data rVal1,
                       Data rVal2, Addr pc);
  ExecInst eInst = ?;
  Data aluVal2   = fromMaybe(rVal2, dInst.imm);

  let aluRes     = alu(rVal1, aluVal2, dInst.aluFunc);
  eInst.iType    = dInst.iType;
  eInst.data     = case (dInst.iType)
                     St : rVal2;
                     J, Jr: (pc+4);
                     Auipc: (pc+fromMaybe(?, dInst.imm));
                     default: aluRes; endcase

  let brTaken    = aluBr(rVal1, rVal2, dInst.brFunc);
  let brAddr     = brAddrCalc(pc, rVal1, dInst.iType,
                     fromMaybe(?, dInst.imm), brTaken);
  eInst.brTaken  = brTaken;
  eInst.addr     = (dInst.iType==Ld || dInst.iType==St)?
                     aluRes : brAddr;
  eInst.dst      = dInst.dst;
  return eInst;
endfunction
```

Needed to load PC into a register

Single-Cycle SMIPS *atomic state updates*

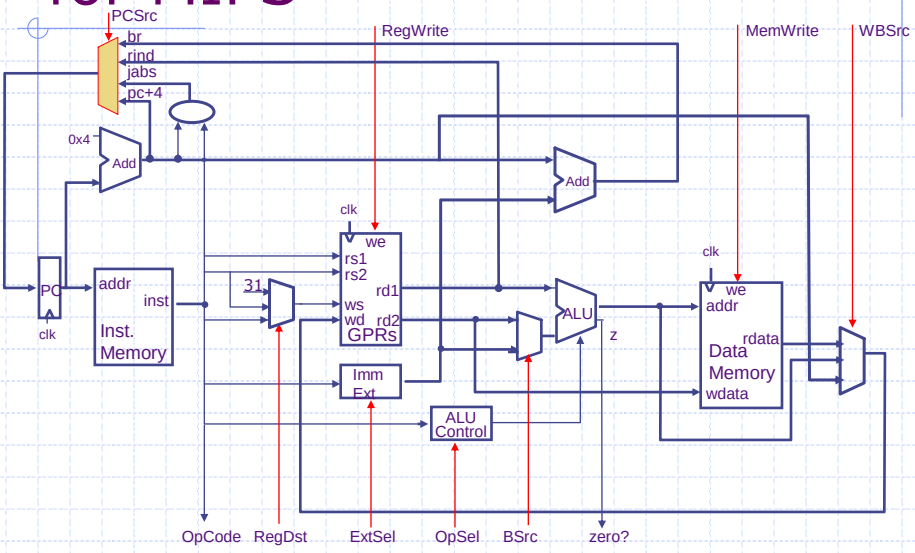
```
  if(eInst.iType == Ld)
    eInst.data <- dMem.req(MemReq{op: Ld,
                    addr: eInst.addr, data: ?});
  else if (eInst.iType == St)
    let dummy <- dMem.req(MemReq{op: St,
                    addr: eInst.addr, data: data});

  if(isValid(eInst.dst))
      rf.wr(fromMaybe(?, eInst.dst), eInst.data);

  pc <= eInst.brTaken ? eInst.addr : pc + 4;

endrule
endmodule
```

state updates

The whole processor is described using one rule; lots of big combinational functions

Harvard-Style Datapath for MIPS

old way



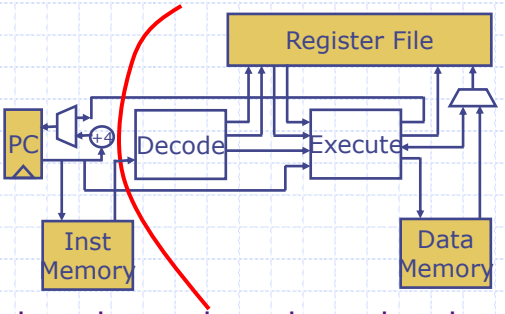
old way

Hardwired Control Table

Opcode	ExtSel	BSrc	OpSel	MemW	RegW	WBSrc	RegDst	PCSrc
ALU	*	Reg	Func	no	yes	ALU	rd	pc+4
ALUi	$sExt_{16}$	Imm	Op	no	yes	ALU	rt	pc+4
ALUiu	$uExt_{16}$	Imm	Op	no	yes	ALU	rt	pc+4
LW	$sExt_{16}$	Imm	+	no	yes	Mem	rt	pc+4
SW	$sExt_{16}$	Imm	+	yes	no	*	*	pc+4
$BEQZ_{z=0}$	$sExt_{16}$	*	0?	no	no	*	*	br
$BEQZ_{z=1}$	$sExt_{16}$	*	0?	no	no	*	*	pc+4
J	*	*	*	no	no	*	*	jabs
JAL	*	*	*	no	yes	PC	R31	jabs
JR	*	*	*	no	no	*	*	rind
JALR	*	*	*	no	yes	PC	R31	rind

BSrc = Reg / Imm WBSrc = ALU / Mem / PC
RegDst = rt / rd / R31 PCSrc = pc+4 / br / rind / jabs

Single-Cycle RISC-V: *Clock Speed*



$t_{Clock} > t_M + t_{DEC} + t_{RF} + t_{ALU} + t_M + t_{WB}$

We can improve the clock speed if we execute each instruction in two clock cycles

$t_{Clock} > \max \{t_M , (t_{DEC} + t_{RF} + t_{ALU} + t_M + t_{WB})\}$

However, this may not improve the performance because each instruction will now take two cycles to execute

Structural Hazards

- Sometimes multicycle implementations are necessary because of resource conflicts, aka, *structural hazards*
  - Princeton style architectures use the same memory for instruction and data and consequently, require at least two cycles to execute Load/Store instructions
  - If the register file supported less than 2 reads and one write concurrently then most instructions would take more than one cycle to execute
- Usually extra registers are required to hold values between cycles

Extras Slides on Decoding

Instruction Formats

- R-type instruction

7	5	5	3	5	7
funct7	rs2	rs1	funct3	rd	opcode

- I-type instruction & I-immediate (32 bits)

12	5	3	5	7
imm[11:0]	rs1	funct3	rd	opcode

I-imm = signExtend(inst[31:20])

- S-type instruction & S-immediate (32 bits)

7	5	5	3	5	7
imm[11:5]	rs2	rs1	funct3	imm[4:0]	opcode

S-imm = signExtend({inst[31:25], inst[11:7]})

Instruction Formats *cont.*

- SB-type instruction & B-immediate (32 bits)

1	6	5	5	3	4	1	7
imm[12]	imm[10:5]	rs2	rs1	funct3	imm[4:1]	imm[11]	opcode

B-imm = signExtend({inst[31], inst[7], inst[30:25], inst[11:8], 1'b0})

- U-type instruction & U-immediate (32 bits)

20	5	7
imm[31:12]	rd	opcode

U-imm = signExtend({inst[31:12], 12'b0})

- UJ-type instruction & J-immediate (32 bits)

1	10	1	8	5	7
imm[20]	imm[10:1]	imm[11]	imm[19:12]	rd	opcode

J-imm = signExtend({inst[31], inst[19:12], inst[20], inst[30:21], 1'b0})

Computational Instructions *cont.*

- Register-immediate instructions (U-type)

20	5	7
imm[31:12]	rd	opcode

  - opcode = LUI : rd ← U-imm
  - opcode = AUIPC : rd ← pc + U-imm
  - U-imm = {inst[31:12], 12'b0}

Decoding Instructions

```
case (opcode)
    opOpImm: …
    opOp: …
    opLui: …
    opAuipc: …
    opJal: …
    opJalr: …
    opBranch: …
    opLoad: …
    opStore: …
    default: … // Unsupported
endcase;
```

```
// opcode
Bit#(7) opOpImm  = 7'b0010011;
Bit#(7) opOp     = 7'b0110011;
Bit#(7) opLui    = 7'b0110111;
Bit#(7) opAuipc  = 7'b0010111;
Bit#(7) opJal    = 7'b1101111;
Bit#(7) opJalr   = 7'b1100111;
Bit#(7) opBranch = 7'b1100011;
Bit#(7) opLoad   = 7'b0000011;
Bit#(7) opStore  = 7'b0100011;
```


Decoding Instructions: Computational Instructions - Imm

```
opOpImm: begin
    dInst.iType = Alu;
    dInst.aluFunc = case (funct3)
        fnADD:  Add;
        fnSLTU: Sltu;
        …
        fnSLL:  Sll;
        fnSR:   aluSel == 0 ? Srl : Sra;
    endcase;
    dInst.brFunc = NT;
    dInst.dst = Valid rd;
    dInst.src1 = Valid rs1;
    dInst.src2 = Invalid;
    dInst.imm = Valid immI;
end
```

Decoding Instructions: Computational Instructions *cont.*

```
opLui: begin // rd = immU + r0
    dInst.iType = Alu;
    dInst.aluFunc = Add;
    dInst.brFunc = NT;
    dInst.dst = tagged Valid rd;
    dInst.src1 = tagged Valid 0;
    dInst.src2 = tagged Invalid;
    dInst.imm = tagged Valid immU;
end
opAuipc: begin
    dInst.iType = Auipc;
    dInst.aluFunc = ?;
    dInst.brFunc = NT;
    dInst.dst = tagged Valid rd;
    dInst.src1 = tagged Invalid;
    dInst.src2 = tagged Invalid;
    dInst.imm = tagged Valid immU;
end
```


Decoding Instructions: Unconditional Jumps

```
opJal: begin
    dInst.iType = J;
    dInst.aluFunc = ?;
    dInst.brFunc = AT;
    dInst.dst = Valid rd;
    dInst.src1 = Invalid;
    dInst.src2 = Invalid;
    dInst.imm = Valid immJ;
end
opJalr: begin
    dInst.iType = Jr;
    dInst.aluFunc = ?;
    dInst.brFunc = AT;
    dInst.dst = Valid rd;
    dInst.src1 = Valid rs1;
    dInst.src2 = Invalid;
    dInst.imm = Valid immI;
end
```

Decoding instructions: Unsupported

```
default: begin
    dInst.iType = Unsupported;
    dInst.aluFunc = ?;
    dInst.brFunc = NT;
    dInst.dst = Invalid;
    dInst.src1 = Invalid;
    dInst.src2 = Invalid;
    dInst.imm = Invalid;
end
```


Branch Address Calculation

```
function Addr brAddrCalc(Addr pc, Data val,
            IType iType, Data imm, Bool taken);
  Addr pcPlus4 = pc + 4;
  Addr targetAddr = case (iType)
    J  : {pc + imm};
    Jr : {truncateLSB(val + imm), 1'b0};
    Br : (taken ? pc + imm : pcPlus4);
    default: pcPlus4;
  endcase;
  return targetAddr;
endfunction
```