A Processor

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CS 3410, Spring 2010
Computer Science
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See: P&H Chapter 2.16-20, 4.1-3

Announcements

HW2 available later today

HW2 due in one week and a half

Work alone

Use your resources

- FAQ, class notes, book, Sections, office hours, newsgroup, CSUGLab

Make sure you

- Registered for class, can access CMS, have a Section, and have a project partner
- Check online syllabus/schedule, review slides and lecture notes, Office Hours, early homework and programming assignments

Announcements

Prelims: ~~Evening~~ of Thursday, March 10 and April 28th

Late Policy

1) Each person has a total of four “slip days”

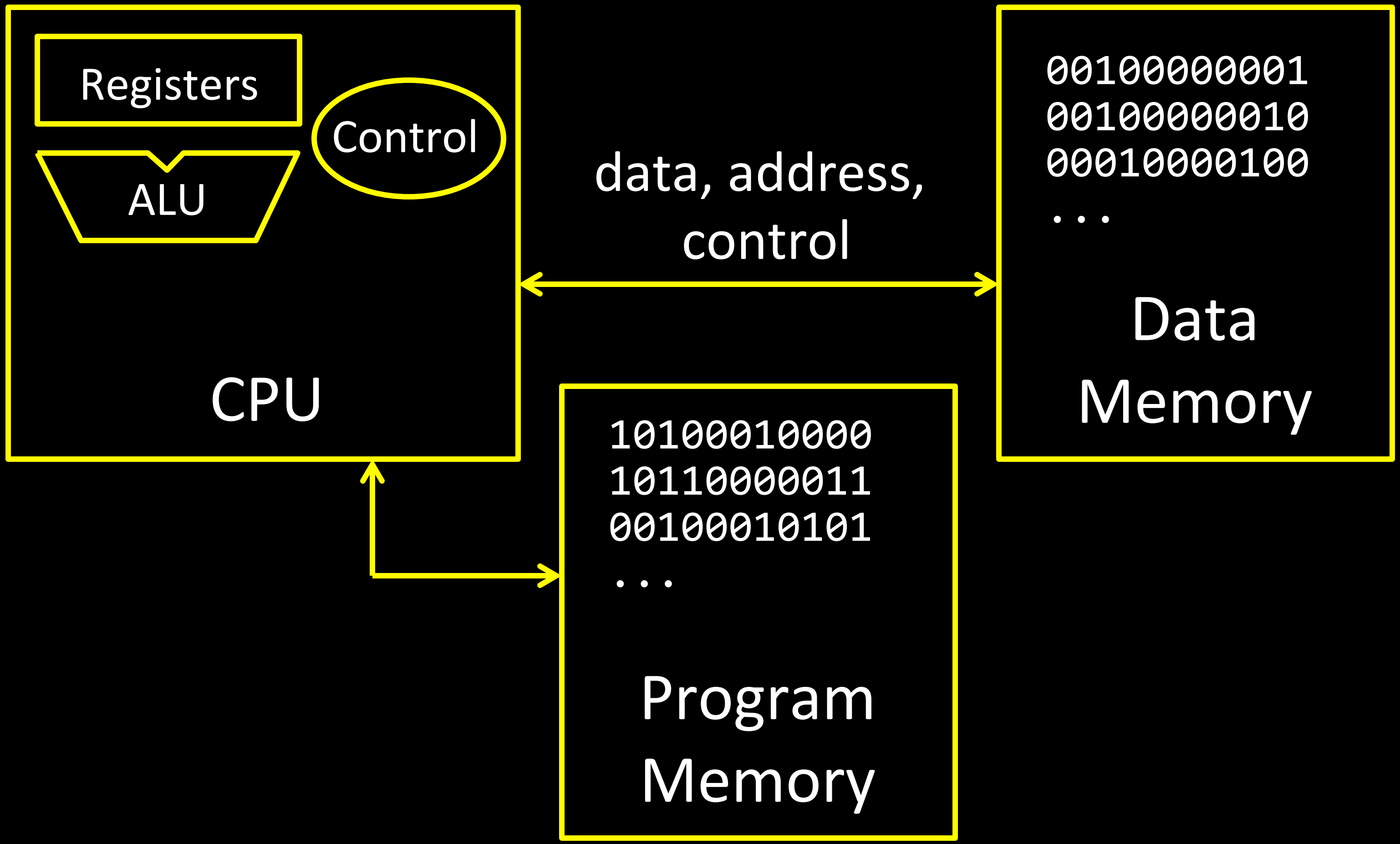
2) For projects, slip days are deducted from all partners

3) 10% deducted per day late after slip days are exhausted

Basic Computer System

Let's build a MIPS CPU

- ...but using (modified) Harvard architecture



Instructions

```
    for (i = 0; i < 10; i++)
        printf(“go cucs”);
```

```
main:  addi r2, r0, 10
       addi r1, r0, 0
loop:  slt r3, r1, r2
       ...
```

```
00100000000000100000000000001010
00100000000000010000000000000000
00000000001000100001100000101010
```

High Level Language

- C, Java, Python, Ruby, …
- Loops, control flow, variables

Assembly Language

- No symbols (except labels)
- One operation per statement

Machine Langauge

- Binary-encoded assembly
- Labels become addresses

Instruction Types

Arithmetic

- add, subtract, shift left, shift right, multiply, divide

Memory

- load value from memory to a register
- store value to memory from a register

Control flow

- unconditional jumps
- conditional jumps (branches)
- jump and link (subroutine call)

Many other instructions are possible

- vector add/sub/mul/div, string operations
- manipulate coprocessor
- I/O

Complexity

MIPS = Reduced Instruction Set Computer (RISC)

- ≈ 200 instructions, 32 bits each, 3 formats
  - mostly orthogonal
- all operands in registers
  - almost all are 32 bits each, can be used interchangeably
- ≈ 1 addressing mode: Mem[reg + imm]

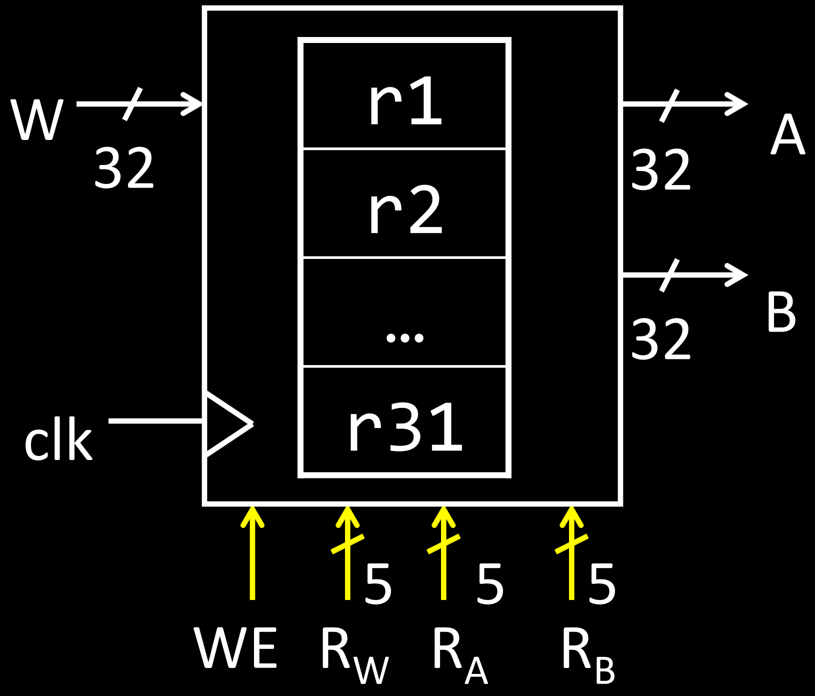
x86 = Complex Instruction Set Computer (CISC)

- > 1000 instructions, 1 to 15 bytes each
- operands in special registers, general purpose registers, memory, on stack, …
  - can be 1, 2, 4, 8 bytes, signed or unsigned
- 10s of addressing modes
  - e.g. Mem[segment + reg + reg*scale + offset]

MIPS Register file

MIPS register file

- 32 registers, 32-bits each (with r0 wired to zero)
- Write port indexed via R_W
  - Writes occur on falling edge but only if WE is high
- Read ports indexed via R_A, R_B



MIPS Memory

MIPS Memory

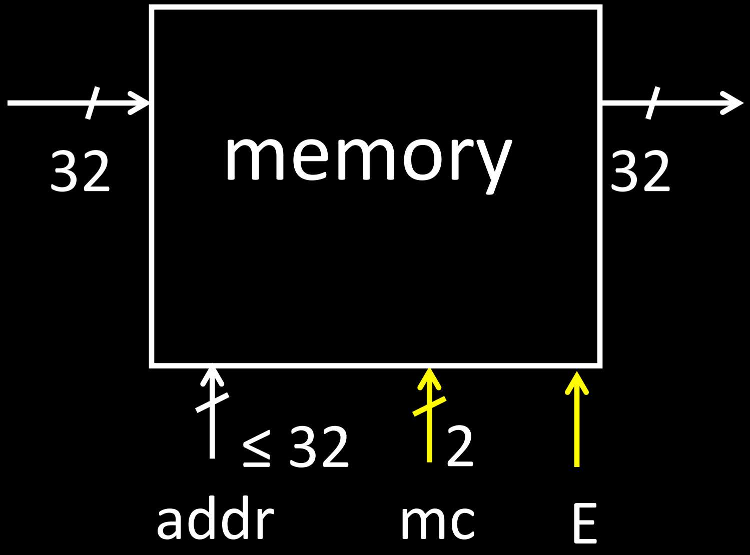
- Up to 32-bit address
- 32-bit data
  (but byte addressed)
- Enable + 2 bit memory control

  00: read word (4 byte aligned)

  01: write byte

  10: write halfword (2 byte aligned)

  11: write word (4 byte aligned)



Instruction Usage

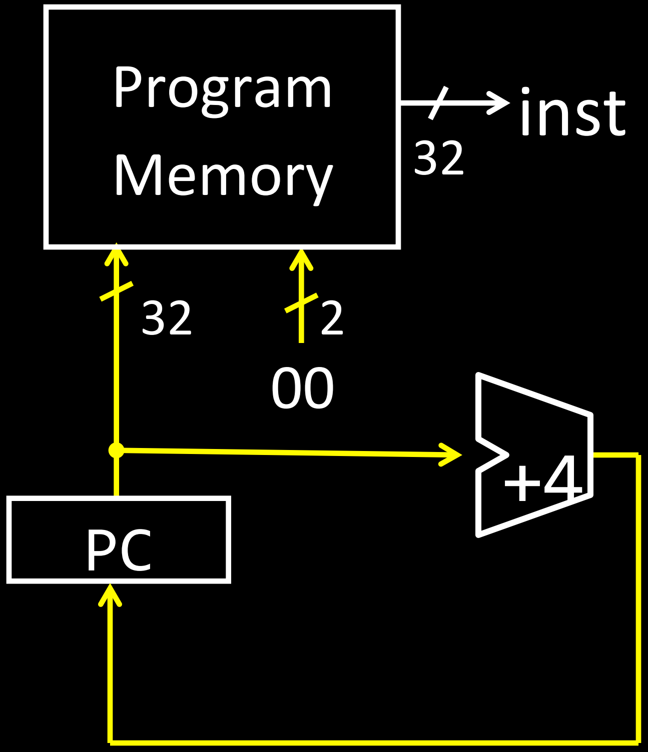
Basic CPU execution loop

1. fetch one instruction
2. increment PC
3. decode
4. execute

Instruction Fetch

Instruction Fetch Circuit

- Fetch instruction from memory
- Calculate address of next instruction
- Repeat



Arithmetic Instructions

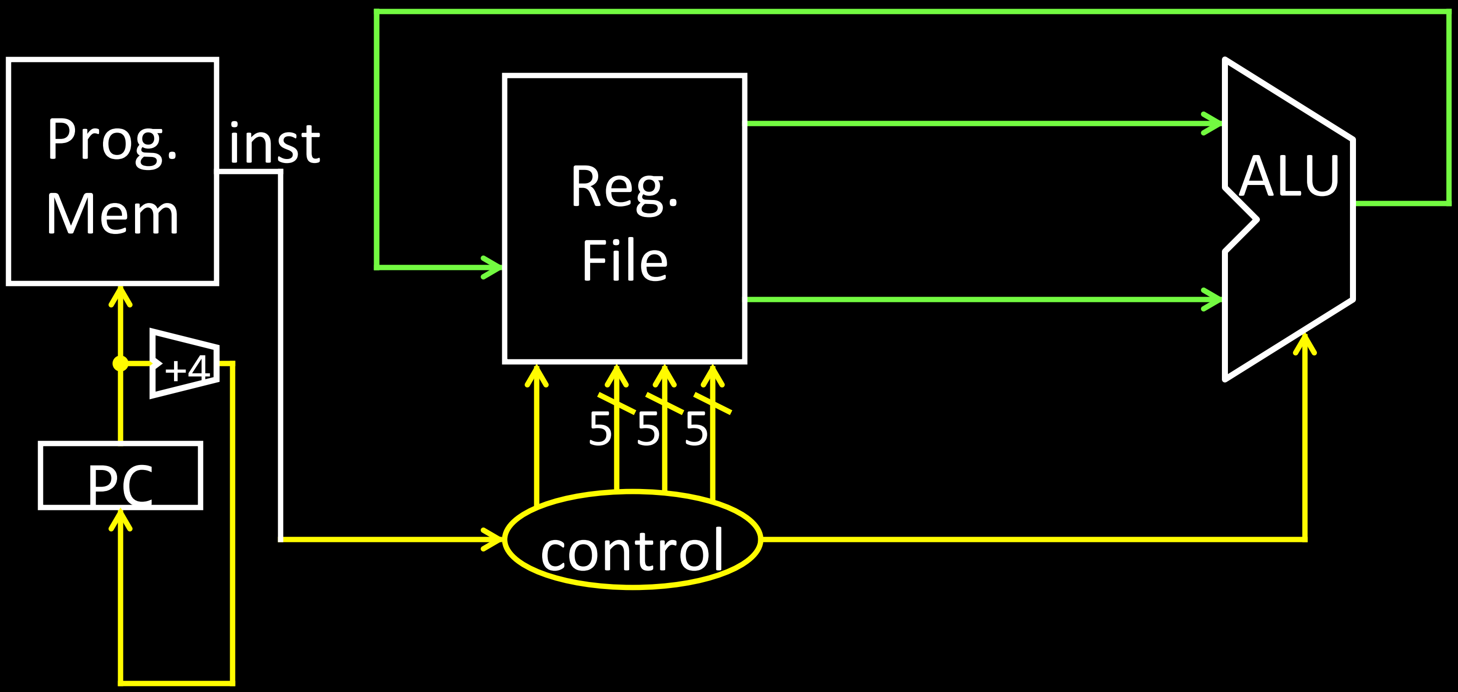
`00000001000001100010000000100110`

op	rs	rt	rd	-	func
6 bits	5 bits	5 bits	5 bits	5 bits	6 bits

R-Type

op	func	mnemonic	description
0x0	0x21	ADDU rd, rs, rt	R[rd] = R[rs] + R[rt]
0x0	0x23	SUBU rd, rs, rt	R[rd] = R[rs] – R[rt]
0x0	0x25	OR rd, rs, rt	R[rd] = R[rs] | R[rt]
0x0	0x26	XOR rd, rs, rt	R[rd] = R[rs] ⊕ R[rt]
0x0	0x27	NOR rd, rs rt	R[rd] = ~ (R[rs] | R[rt])

Arithmetic and Logic



Example Programs

r4 = (r1 + r2) | r3

r8 = 4*r3 + r4 – 1

r9 = 9

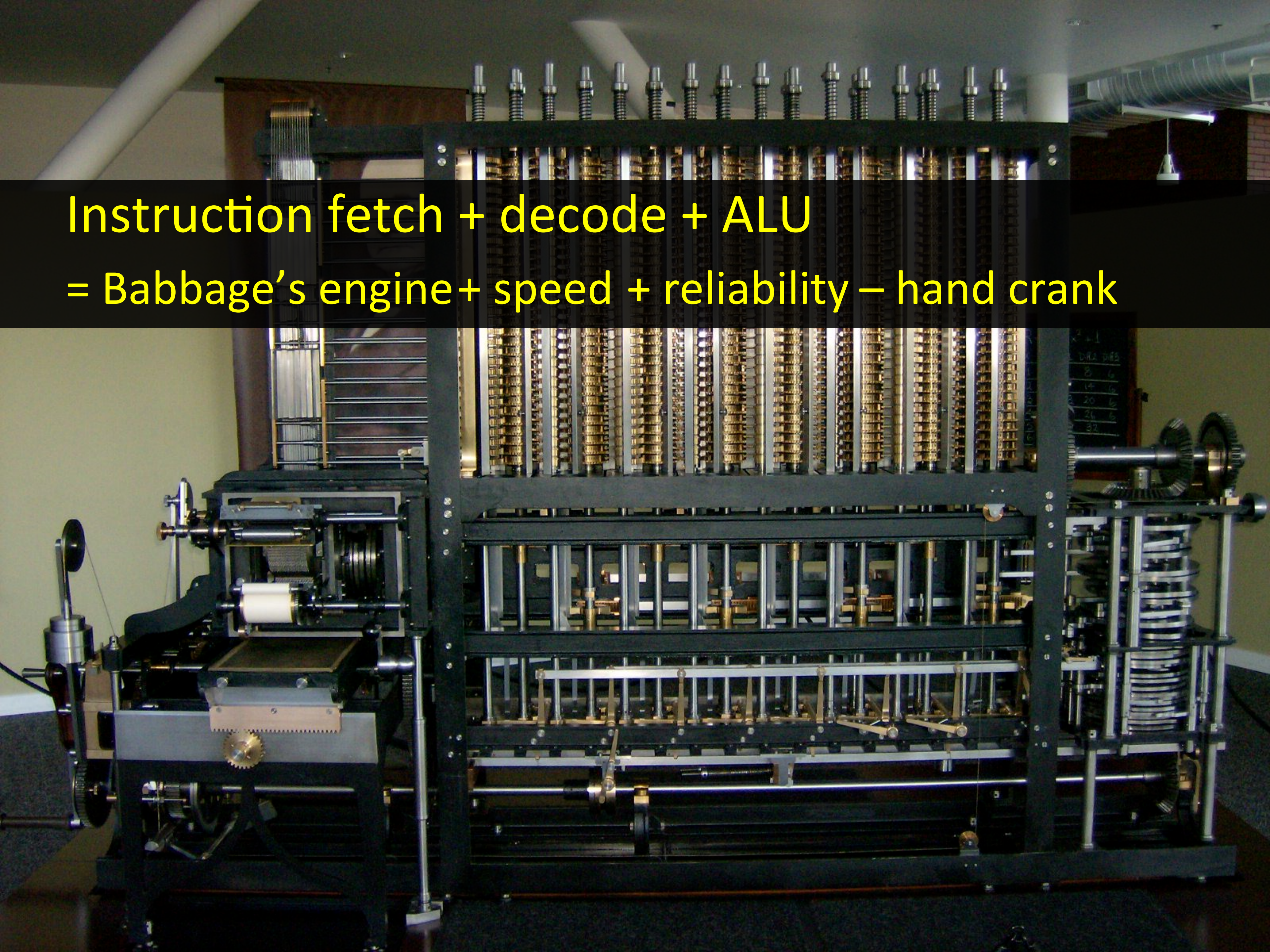
ADDU rd, rs, rt

SUBU rd, rs, rt

OR rd, rs, rt

XOR rd, rs, rt

NOR rd, rs rt



Instruction fetch + decode + ALU

= Babbage’s engine+ speed + reliability – hand crank

Arithmetic Instructions: Shift

```
00000000000001000100000110000011
```

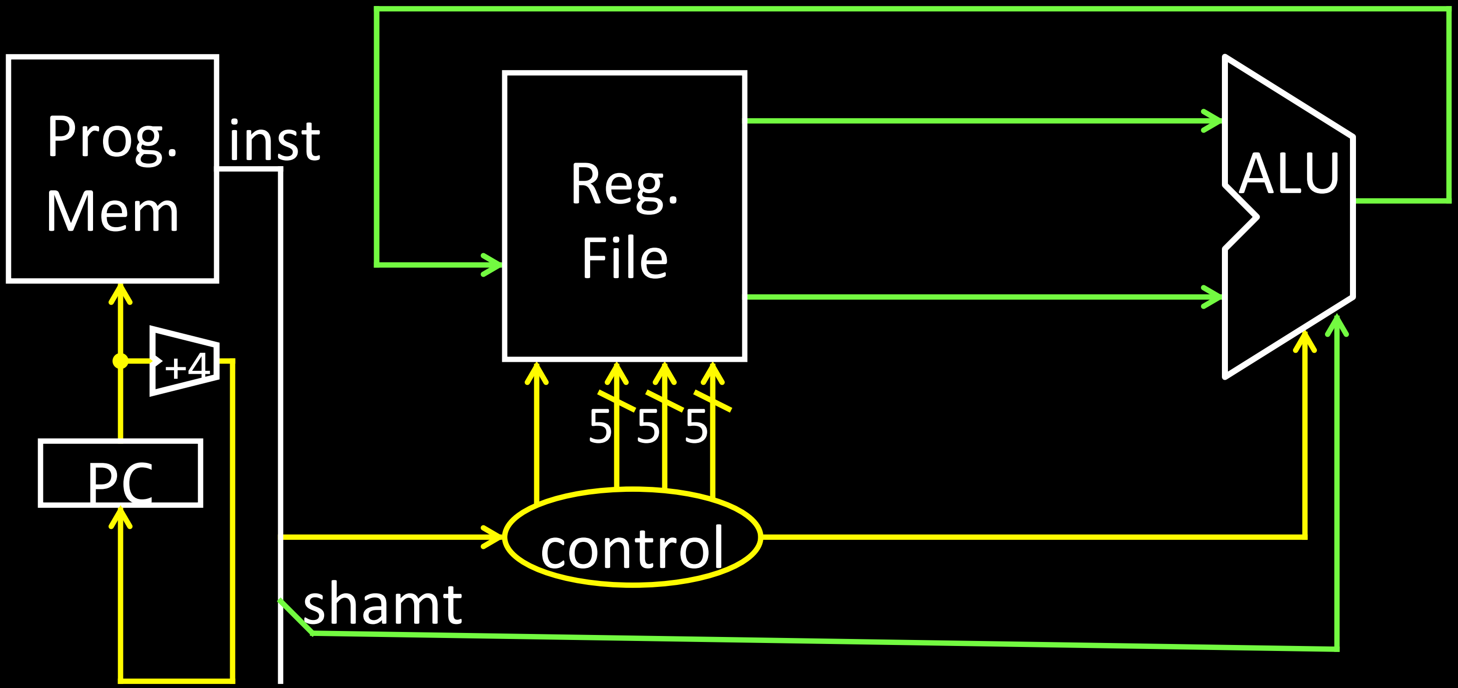
op	-	rt	rd	shamt	func
6 bits	5 bits	5 bits	5 bits	5 bits	6 bits

R-Type

op	**func**	**mnemonic**	**description**
0x0	0x0	SLL rd, rs, shamt	R[rd] = R[rt] << shamt
0x0	0x2	SRL rd, rs, shamt	R[rd] = R[rt] >>> shamt (zero ext.)
0x0	0x3	SRA rd, rs, shamt	R[rd] = R[rs] >> shamt (sign ext.)

ex: r5 = r3 * 8

Shift



Arithmetic Instructions: Immediates

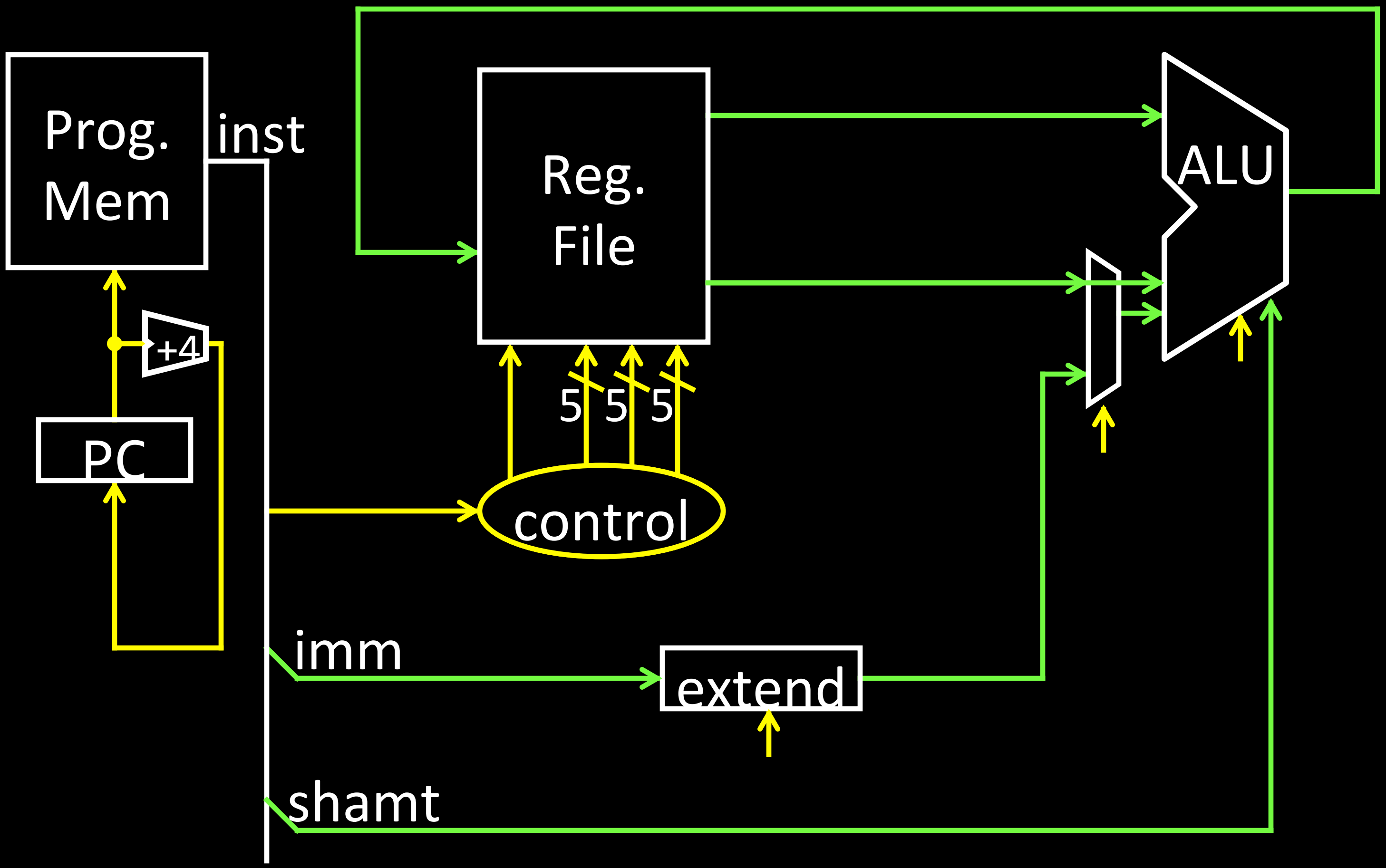
$$\underbrace{\texttt{001001}}_{\substack{\texttt{op} \\ \text{6 bits}}}\underbrace{\texttt{00101}}_{\substack{\texttt{rs} \\ \text{5 bits}}}\underbrace{\texttt{00101}}_{\substack{\texttt{rd} \\ \text{5 bits}}}\underbrace{\texttt{0000000000000101}}_{\substack{\texttt{immediate} \\ \text{16 bits}}}$$

I-Type

op	**mnemonic**	**description**
0x9	ADDIU rd, rs, imm	R[rd] = R[rs] + sign_extend(imm)
0xc	ANDI rd, rs, imm	R[rd] = R[rs] & zero_extend(imm)
0xd	ORI rd, rs, imm	R[rd] = R[rs] | zero_extend(imm)

ex: r5 += 5 ex: r9 = -1 ex: r9 = 65535

Immediates



Arithmetic Instructions: Immediates

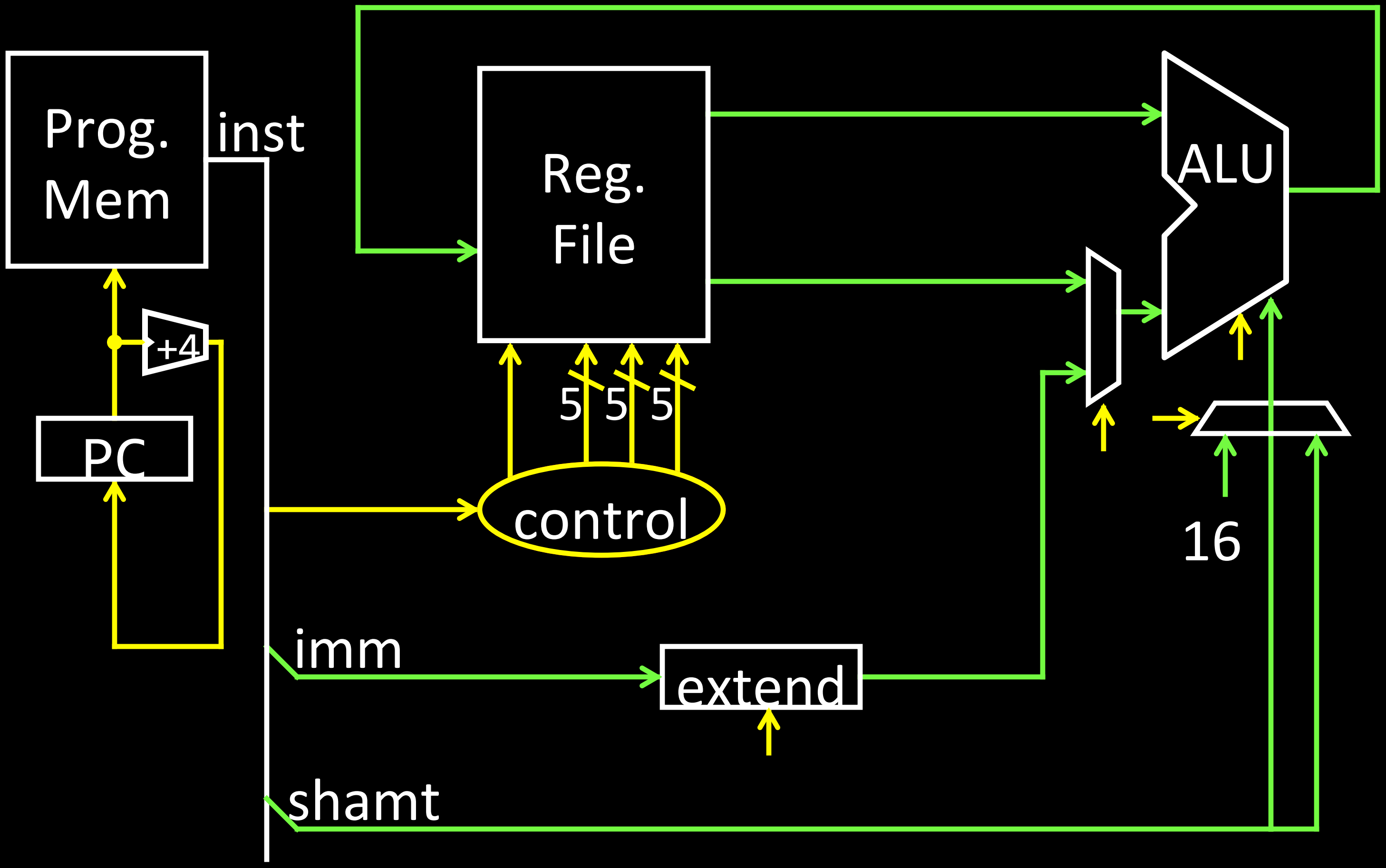
001111	00000	00101	0000000000000101
op	-	rd	immediate
6 bits	5 bits	5 bits	16 bits

I-Type

op	mnemonic	description
0xF	LUI rd, imm	R[rd] = imm << 16

ex: r5 = 0xdeadbeef

Immediates


Prog. Mem
inst
+4
PC
Reg. File
5
5
5
control
ALU
16
imm
extend
shamt

MIPS Instruction Types

Arithmetic/Logical

- R-type: result and two source registers, shift amount
- I-type: 16-bit immediate with sign/zero extension

Memory Access

- load/store between registers and memory
- word, half-word and byte operations

Control flow

- conditional branches: pc-relative addresses
- jumps: fixed offsets, register absolute

Memory Instructions

$$\underbrace{101001}\underbrace{00101}\underbrace{00001}\underbrace{0000000000000010}$$

op	rs	rd	offset
6 bits	5 bits	5 bits	16 bits

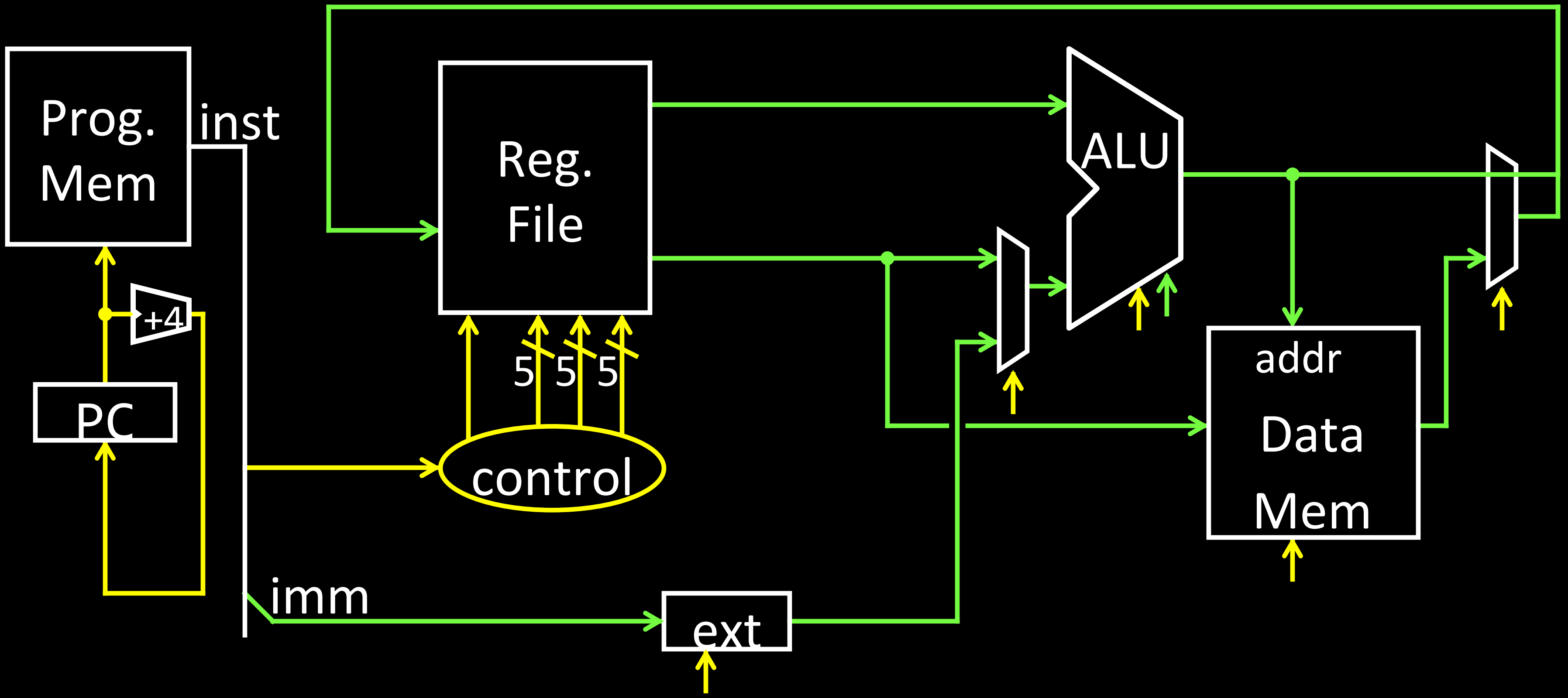
I-Type

base + offset addressing

op	mnemonic	description
0x20	LB rd, offset(rs)	R[rd] = sign_ext(Mem[offset+R[rs]])
0x24	LBU rd, offset(rs)	R[rd] = zero_ext(Mem[offset+R[rs]])
0x21	LH rd, offset(rs)	R[rd] = sign_ext(Mem[offset+R[rs]])
0x25	LHU rd, offset(rs)	R[rd] = zero_ext(Mem[offset+R[rs]])
0x23	LW rd, offset(rs)	R[rd] = Mem[offset+R[rs]]
0x28	SB rd, offset(rs)	Mem[offset+R[rs]] = R[rd]
0x29	SH rd, offset(rs)	Mem[offset+R[rs]] = R[rd]
0x2b	SW rd, offset(rs)	Mem[offset+R[rs]] = R[rd]

signed offsets

Memory Operations



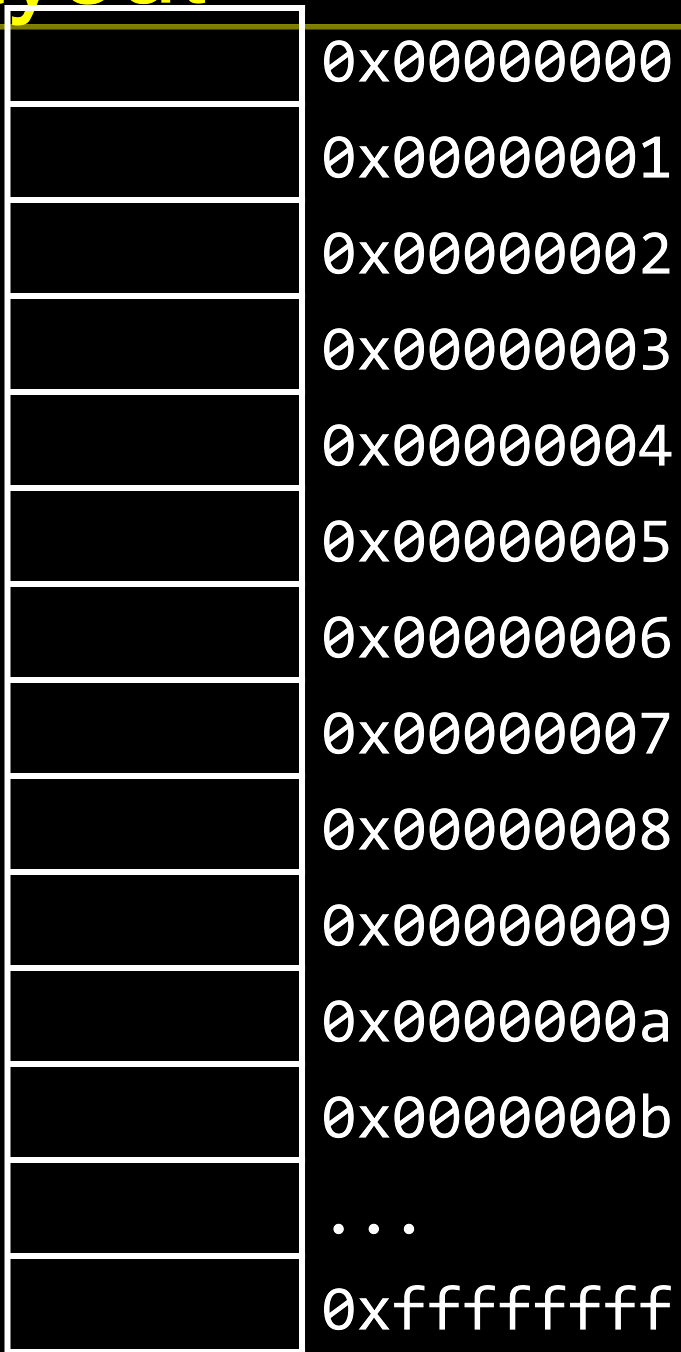
Example

```
int h, A[];
A[12] = h + A[8];
```

Memory Layout

Examples:

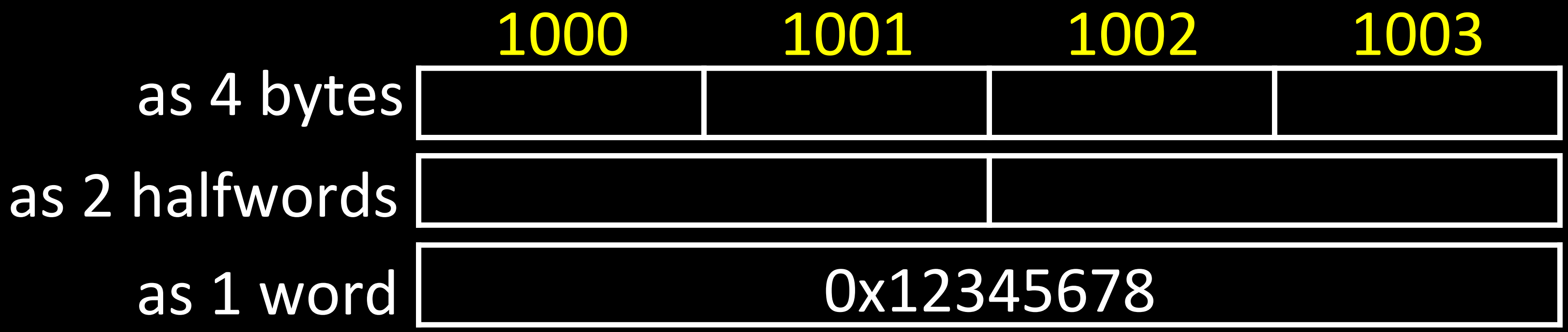
```
# r5 contains 0x5
sb r5, 2(r0)
lb r6, 2(r0)

sw r5, 8(r0)
lb r7, 8(r0)
lb r8, 11(r0)
```



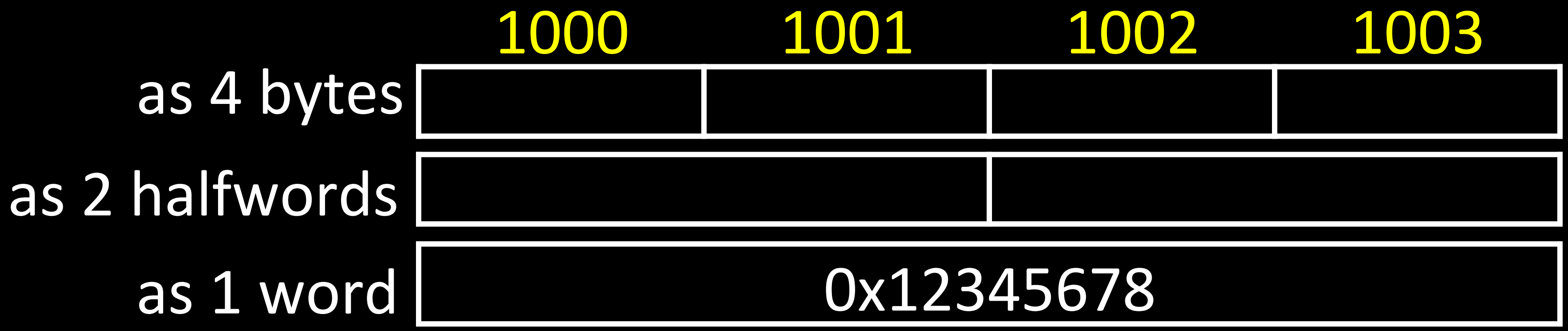
Endianness

Endianness: Ordering of bytes within a memory word

Little Endian = least significant part first (MIPS, x86)



Big Endian = most significant part first (MIPS, networks)



Control Flow: Absolute Jump

$$\underbrace{000010}_{\text{op}}\underbrace{10100001001000011000000011}_{\text{immediate}}$$

op 6 bits — immediate 26 bits

J-Type

op	mnemonic	description
0x2	J target	PC = $(PC+4)_{32..29}$ || target || 00

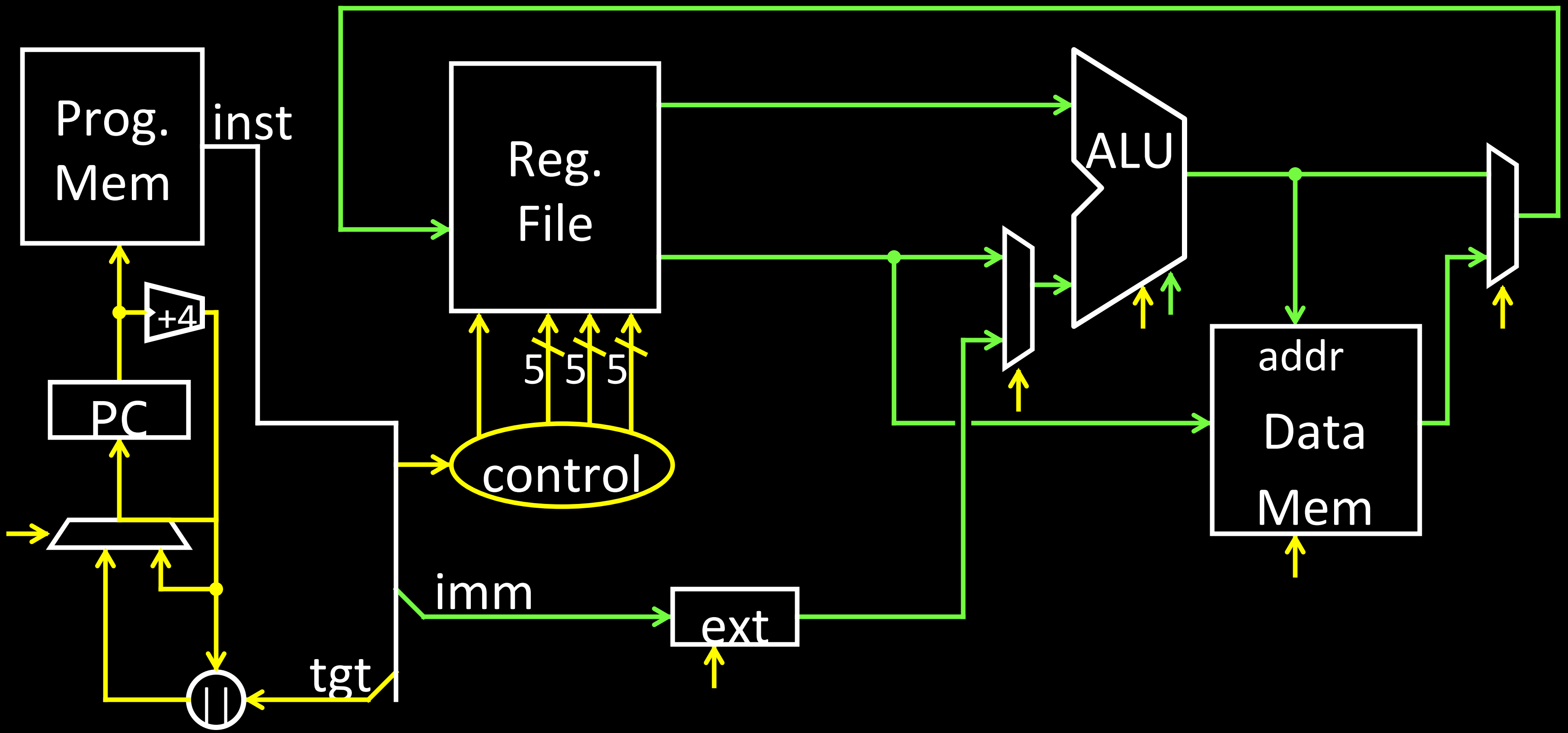
Absolute addressing for jumps

- Jump from 0x30000000 to 0x20000000?
  - But: Jumps from 0x2FFFFFFF to 0x3xxxxxxx are possible, but not reverse
- Trade-off: out-of-region jumps vs. 32-bit instruction encoding

MIPS Quirk:

- jump targets computed using *already incremented* PC

Absolute Jump



Control Flow: Jump Register

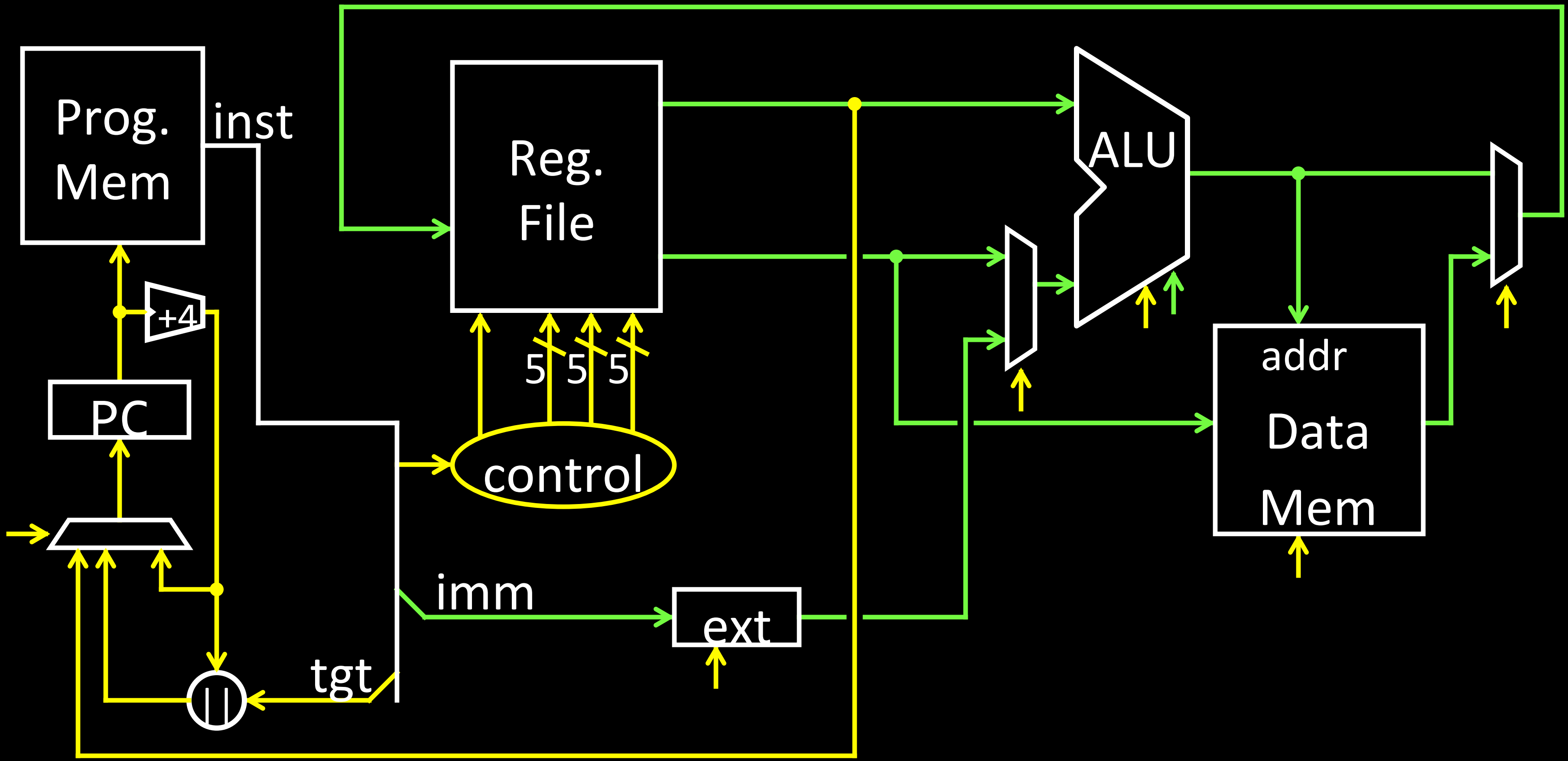
```
00000000011000000000000000001000
```

op	rs	-	-	-	func
6 bits	5 bits	5 bits	5 bits	5 bits	6 bits

R-Type

op	func	mnemonic	description
0x0	0x08	JR rs	PC = R[rs]

Jump Register



Examples (2)

jump to 0xabcd1234

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```
jump to 0xabcd1234


# assume 0 <= r3 <= 1
if (r3 == 0) jump to 0xdecafe0
else jump to 0xabcd1234
```

Examples (2)

```
jump to 0xabcd1234


# assume 0 <= r3 <= 1
if (r3 == 0) jump to 0xdecafe0
else jump to 0xabcd1234
```

Control Flow: Branches

$$\underbrace{000100}_{\texttt{op}}\underbrace{00101}_{\texttt{rs}}\underbrace{00001}_{\texttt{rd}}\underbrace{0000000000000011}_{\texttt{offset}}$$

op	rs	rd	offset
6 bits	5 bits	5 bits	16 bits

I-Type

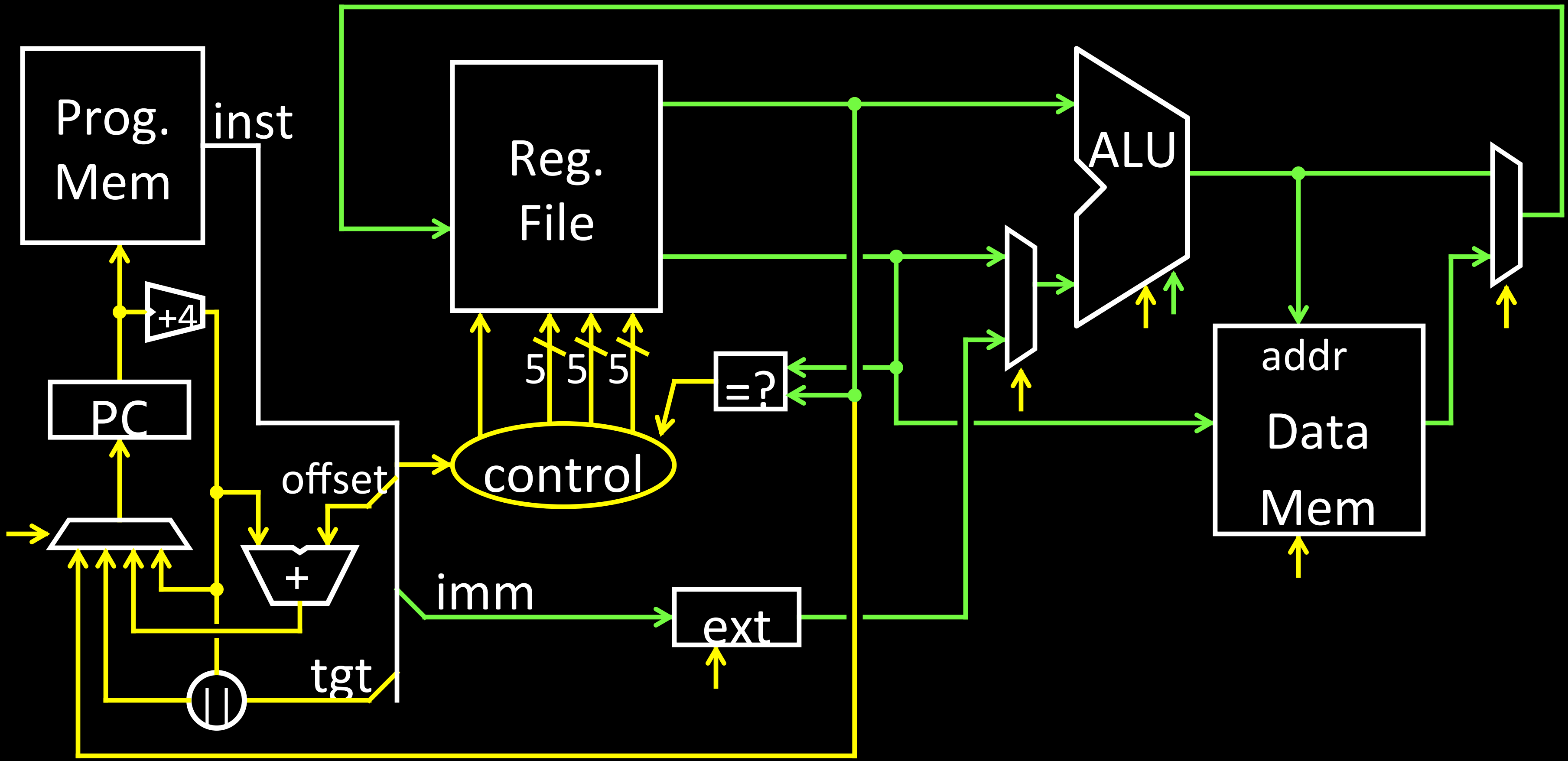
signed offsets

op	mnemonic	description
0x4	BEQ rs, rd, offset	if R[rs] == R[rd] then PC = PC+4 + (offset<<2)
0x5	BNE rs, rd, offset	if R[rs] != R[rd] then PC = PC+4 + (offset<<2)

Examples (3)

```
if (i == j) { i = i * 4; }
else { j = i - j; }
```

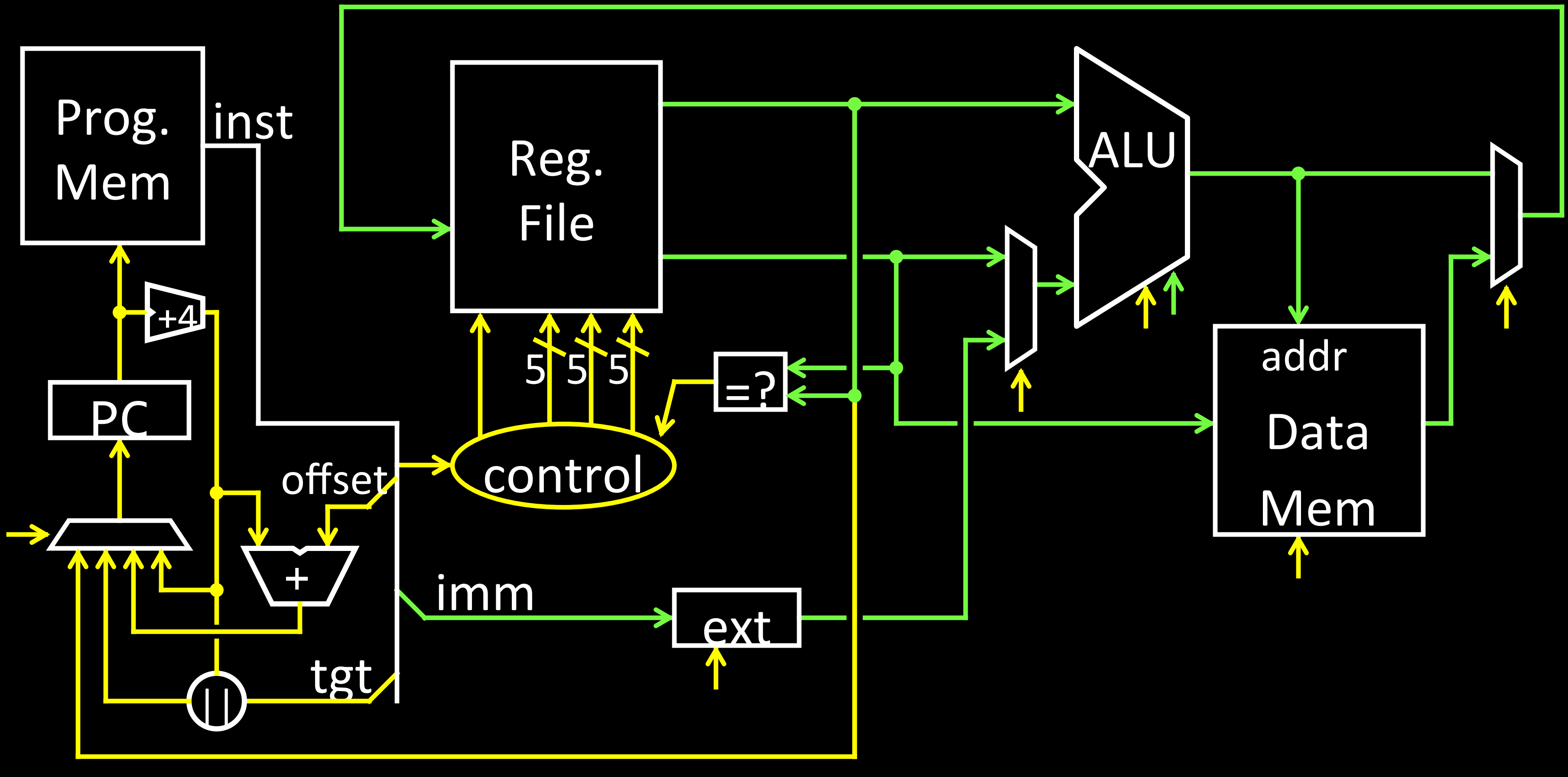
Absolute Jump



Could have used ALU for branch add

Could have used ALU for branch cmp

Absolute Jump



Could have used ALU for branch add

Could have used ALU for branch cmp

Control Flow: More Branches

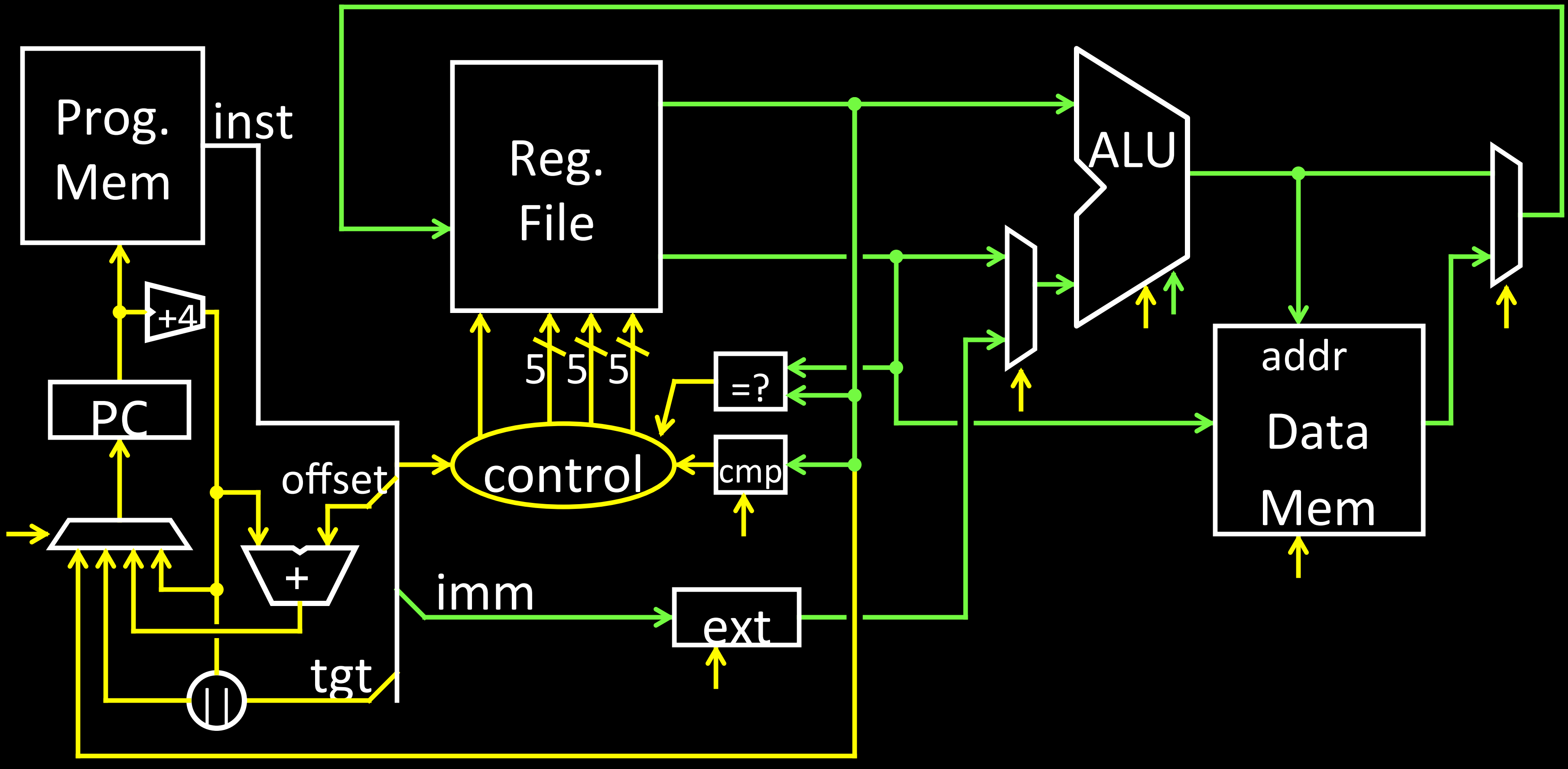
$$\underbrace{000001}_{\substack{\text{op} \\ \text{6 bits}}}\underbrace{00101}_{\substack{\text{rs} \\ \text{5 bits}}}\underbrace{00001}_{\substack{\text{subop} \\ \text{5 bits}}}\underbrace{0000000000000010}_{\substack{\text{offset} \\ \text{16 bits}}}$$

almost I-Type

signed offsets

op	subop	mnemonic	description
0x1	0x0	BLTZ rs, offset	if R[rs] < 0 then PC = PC+4+ (offset<<2)
0x1	0x1	BGEZ rs, offset	if R[rs] ≥ 0 then PC = PC+4+ (offset<<2)
0x6	0x0	BLEZ rs, offset	if R[rs] ≤ 0 then PC = PC+4+ (offset<<2)
0x7	0x0	BGTZ rs, offset	if R[rs] > 0 then PC = PC+4+ (offset<<2)

Absolute Jump



Could have used ALU for branch cmp

Control Flow: Jump and Link

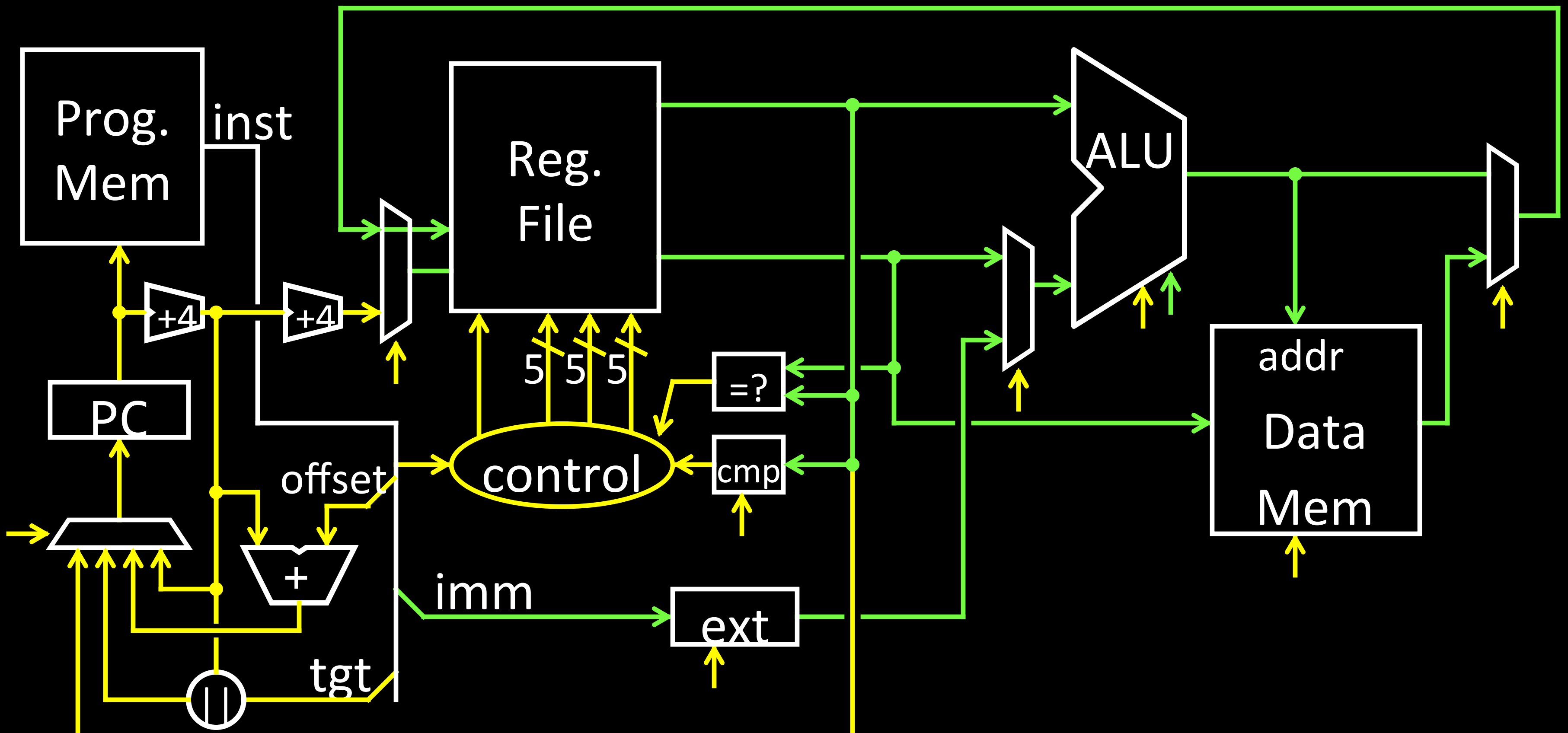
$$\underbrace{000011}_{\substack{\text{op} \\ \text{6 bits}}}\underbrace{00000001001000011000000010}_{\substack{\text{immediate} \\ \text{26 bits}}}$$

J-Type

op	mnemonic	description

0x3	JAL target	r31 = PC+8
		PC = $(PC+4)_{32..29}$ || target || 00

Absolute Jump



Could have used ALU for link add

Next Time

CPU Performance

Pipelined CPU