Computer architecture

The simplest processor

Wouter M. Koolen

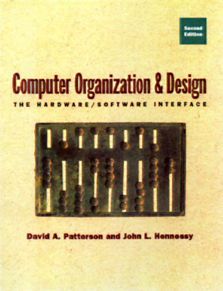
Advanced Topics
23-2-12

About me

- Work in machine learning ...
- .. but generally interested in most of computer science
- Fervent programmer
- Computer architecture as a hobby
- Author of SIM-PL simulator for digital hardware

`http://www.science.uva.nl/amstel/SIM-PL`

Source material



What do I expect of you / What would really help

You ...

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- have seen a digital circuit (e.g. gate, adder, flip-flop).
- wrote a program (e.g. **if**, **goto**, increment)
- are not mortally afraid of bits and hexadecimal

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And most importantly ...

You raise your hand when you get lost

Goal of this lecture

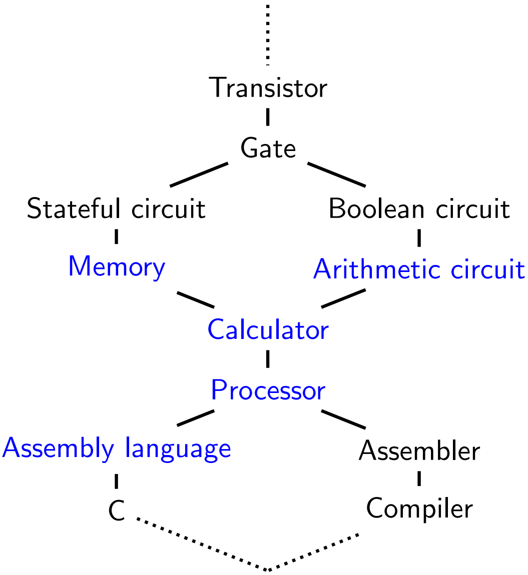
I present the simplest processor

Understanding

- hardware design
  - You can do it too
  - Baseline for more complex designs
  - Many (esoteric) designs found niches
- execution of software
  - Programming (e.g. embedded devices)
  - Compiler architecture
  - The why of hardware eccentricities

Goal of this lecture

Pierce layers of abstraction



Calculator

Goal

- 16 variables (memory cells)
- program (list of instructions)
- 4 operations

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`ADD`, `SUB`, `AND`, `COPY`

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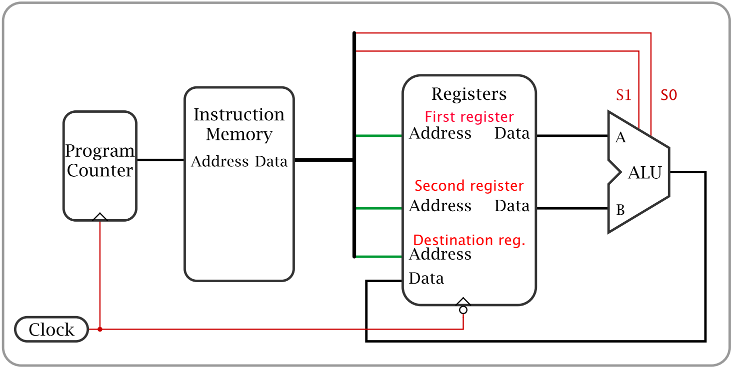
Example program

0:	`ADD`	`$6, $3, $4`	Set Reg6 to Reg3 + Reg4
1:	`SUB`	`$7, $3, $4`	Set Reg7 to Reg3 − Reg4
2:	`COPY`	`$8, $6`	Set Reg8 to Reg6

Implementation: the hardware circuit



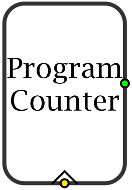
The driving force

Purpose: Synchronise operation of components

- Usually some kind of oscillating crystal
- **Clock** 
- High and low levels
- Positive (up) edge and negative (down) edge
- A *clock cycle* is: up – high – down – low

Program counter

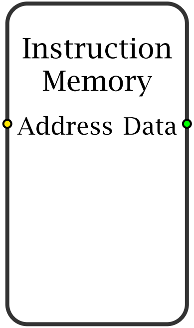
Purpose: maintain the current position in the program



- One address
- Increment triggered by positive clock edge

Instruction memory

Purpose: store the program



- 16 bit address
- 14 bit data

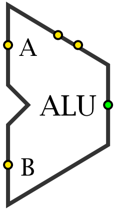
Registers

Purpose: maintain the state of program variables

- 16 registers named `$0, $1, ..., $15`
- 16 bits each
- Two read ports
- One write port (triggered by negative clock edge)

Arithmetic logic unit (ALU)

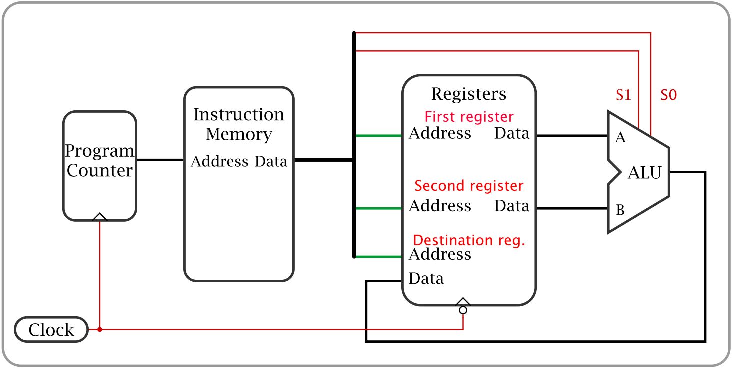
Purpose: performs computation



S_0	S_1	output
0	0	$A + B$
0	1	$A - B$
1	0	$A \& B$
1	1	B

- 2 bits to select operation

Calculator: the circuit



In action

Say $3 initially contains 7, while $4 contains 5.

0:	`ADD`	`$6, $3, $4`	Set Reg6 to Reg3 + Reg4
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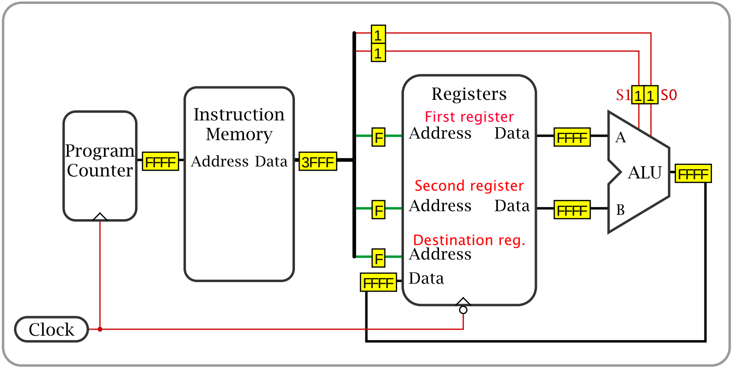

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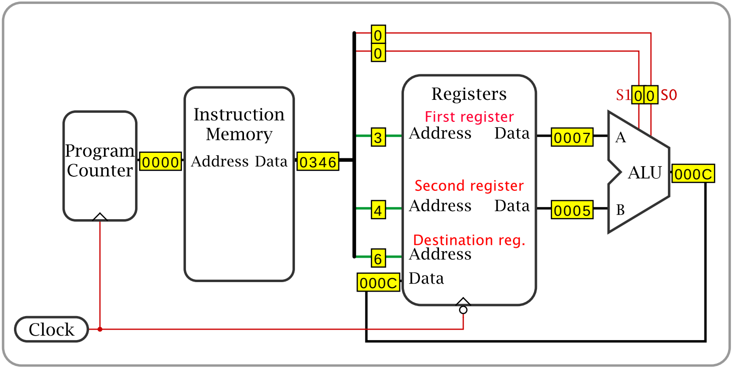

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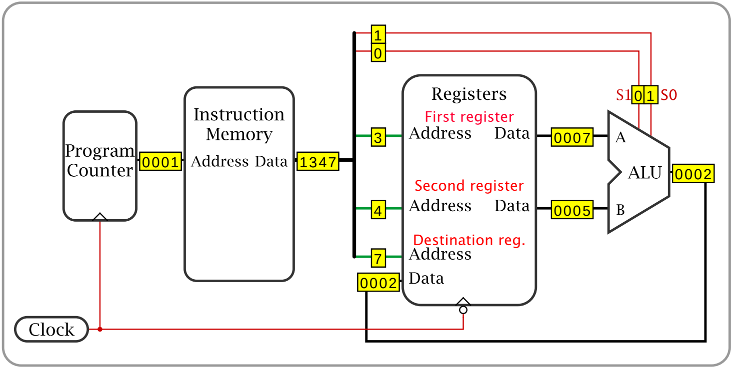

In action

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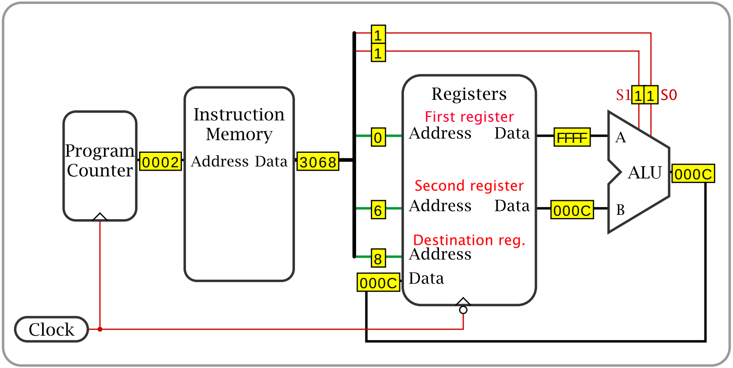
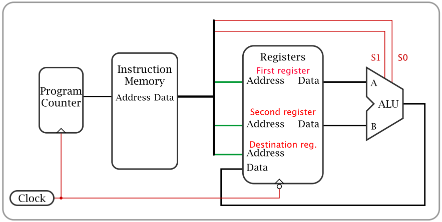


Summary

Calculator

- 16 memory cells
- 4 operations
- Executes program (list of instructions) sequentially
- Timing

(Trick) questions



- Why does an instruction take 14 bits of memory?
- Is `COPY $1, $1` safe?
- What about `ADD $1, $1, $1`?
- Can we increment a register? How?
- Can we multiply 2 registers? How?
- Can we execute an **if** statement? How?

Immediates

Goal
Use of immediates (constants) in instructions

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Instruction set

`ADD`, `SUB`, `AND`, `COPY`, `ADDI`, `SUBI`, `ANDI`, `LOADI`

Immediates

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Use of immediates (constants) in instructions

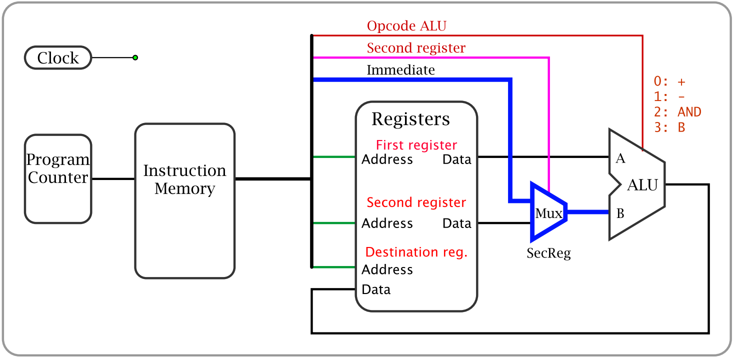
Instruction set

`ADD`, `SUB`, `AND`, `COPY`, `ADDI`, `SUBI`, `ANDI`, `LOADI`

Example program

0:	`LOADI $1, 0x3000`	Load 3000_{hex} in Reg1
1:	`LOADI $2, 0x2000`	Load 2000_{hex} in Reg2
2:	`SUB   $3, $1, $2`	Set Reg3 to Reg1 - Reg2
3:	`ADDI  $4, $3, 0x200`	Set Reg4 to Reg3 $+$ 0200_{hex}

Implementing immediates

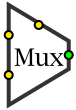


Do we use an immediate?

Immediate value

Multiplexer

Purpose: channel chooser



S	output
0	A
1	B

- 1 bit to select which input is passed on

Immediates in action

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2:	`SUB $3, $1, $2`	Set Reg3 to Reg1 - Reg2
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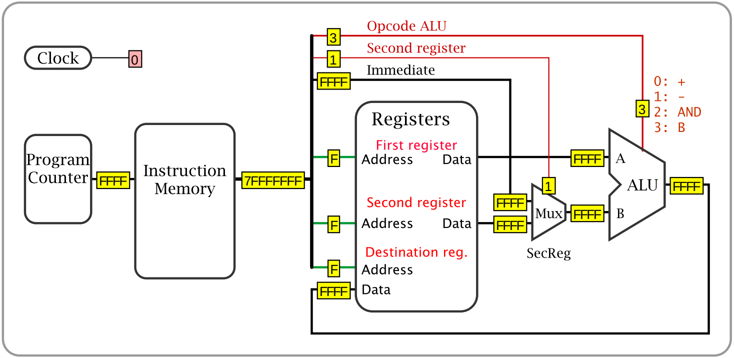

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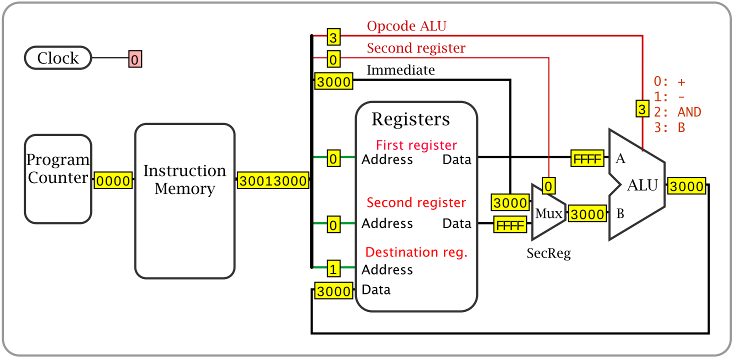

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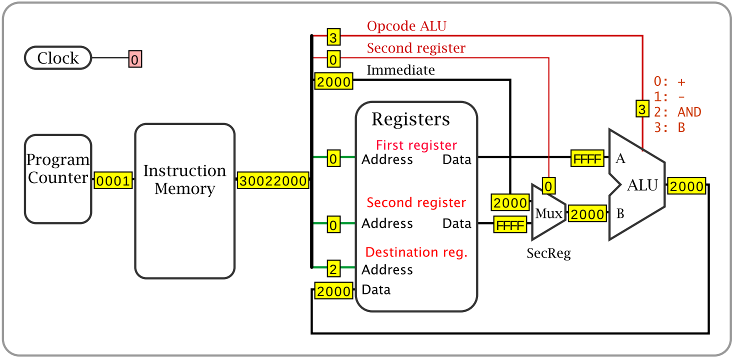

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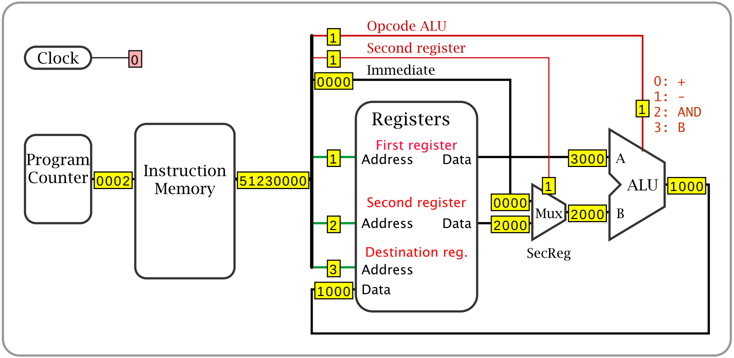

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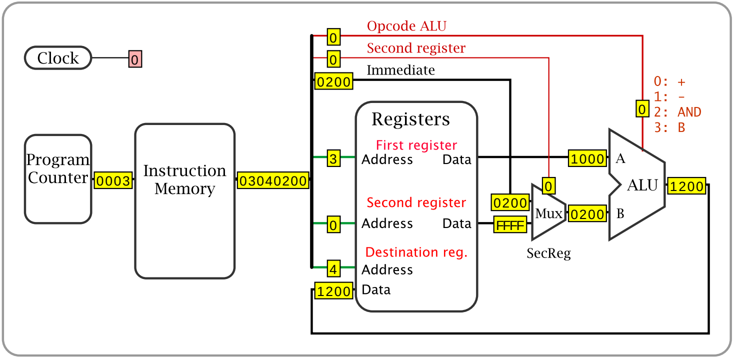
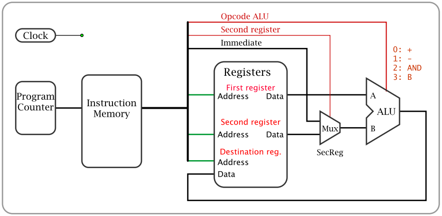


Summary

- A little more hardware ...
- ... to allow immediates as last argument
- Immediates part of instruction

(Trick) questions



- How many bits do we need for each instruction?
- Can we increment a register? How?
- Can we execute `ADDII $1, 0x1, 0x2`? How?
- Can we multiply 2 registers? How?
- Can we execute an **if** statement? How?

Conditional execution and jumps

Goal

Implement **if**/**else**, **switch**, **for**, **while**, **goto** ...

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Instruction set

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Conditional execution and jumps

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Implement **if**/**else**, **switch**, **for**, **while**, **goto** ...

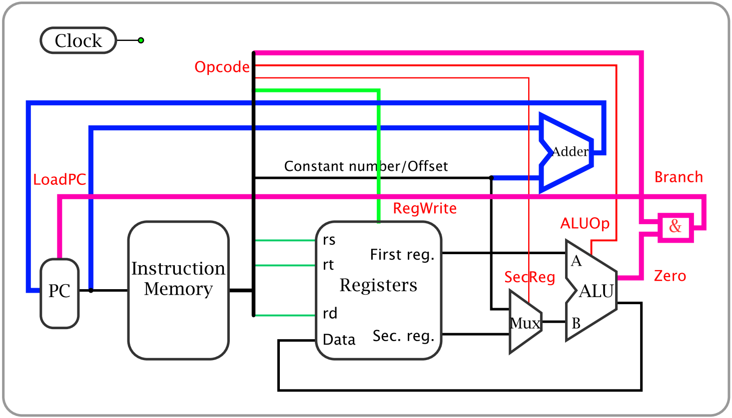
Instruction set

`ADD(I)`, `SUB(I)`, `AND(I)`, `COPY`, `LOADI`, `BRA`, `BZ`, `BEQ`

Example program

```
  LOADI a, 8       # a = 8;
  LOADI b, 4       # b = 4;
  LOADI r, 0       # r = 0;
loop:
  BZ    b, end     # while (b != 0) {
  ADD   r, r, a    #   r += a;
  SUBI  b, b, 1    #   --b;
  BRA   loop       # }
end:
```

Implementing jumps



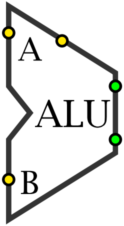
Do we jump?

Where do we jump to?

Do we write to register?

Arithmetic logic unit (ALU)

Purpose: performs computation and tests



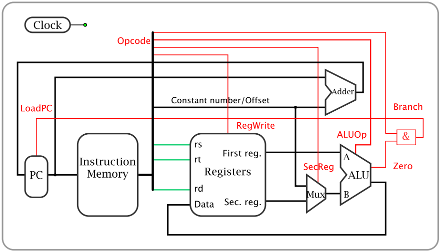
S_0	S_1	output
0	0	$A + B$
0	1	$A - B$
1	0	$A \& B$
1	1	B

- 2 bits to select operation
- Zero bit is set when output is zero

Summary

- A bunch more hardware
- Hardware executes a branch when
  - Instruction is a branch instruction
  - Test succeeds (ALU outputs zero)
- Target of jump is encoded in instruction

(Trick) questions



- How many bits do we need for each instruction?
- How can we test for (with A and B registers)

$$A = 0 \qquad A = 1 \qquad A = B \qquad A \neq B \qquad A < B$$

- Can we multiply 2 registers? How?
- Can we execute an **if** statement? How?
- Can we execute an **if**/**else** statement? How?
- Is Branch the negation of RegWrite?

More/main memory

Goal

Add memory. We add $2^{16} = 65536$ variables

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Instruction set

`ADD(I)`, `SUB(I)`, `AND(I)`, `COPY`, `LOADI`, `BRA`, `BZ`, `BEQ`, `LW`, `SW`

More/main memory

Goal

Add memory. We add $2^{16} = 65536$ variables

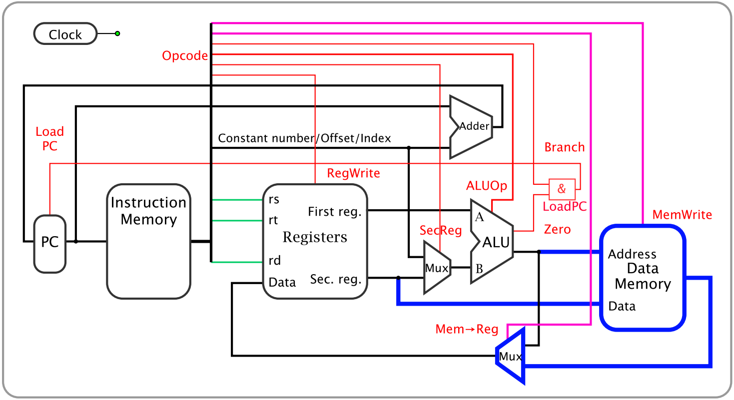
Instruction set

`ADD(I)`, `SUB(I)`, `AND(I)`, `COPY`, `LOADI`, `BRA`, `BZ`, `BEQ`, `LW`, `SW`

Example program

```
LW $1, 10, $6   # Load mem[Reg6 + 10] into Reg1
SW $2, 10, $6   # Store $2 into mem[Reg6 + 10]
```

Implementing main memory



Do we read from/write to memory?

Write what where? Value read?

Summary

- We simply “bolted on” some memory
- Both in hardware
- And in software

(Trick) questions

- How many bits do we need for each instruction?
- Why not simply increase the number of registers?
- Can we perform a computation (say $A + B$) and write the result to memory using a single instruction?
- Can we execute an **if** statement? How?
- What if we want more than $2^{16} = 65536$ variables?
- Can a program modify itself? (polymorphic code)

Procedure calls

Goal

Re-use blocks of code

Procedure calls

Goal

Re-use blocks of code

Instruction set

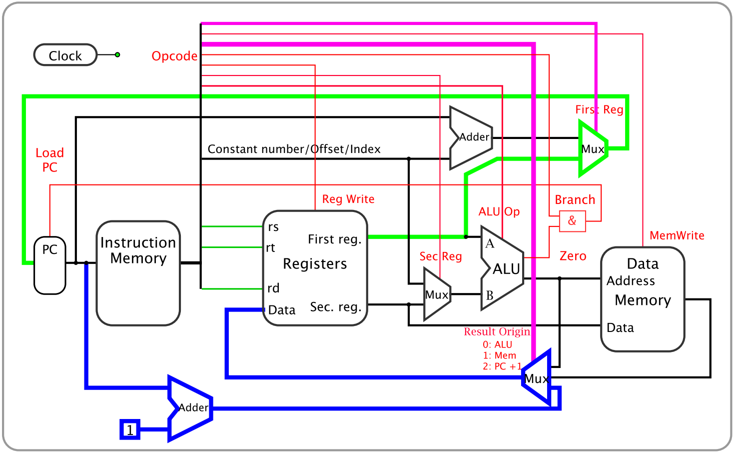
ADD(I), SUB(I), AND(I), COPY, LOADI, BRA, BZ, BEQ, LW, SW, CALL, RETURN

Example program

```
LOADI   $arg1, 1
LOADI   $arg2, 2
LOADI   $arg3, 3
CALL    $ra, Add3

#--------------- Add3 procedure -----------------
Add3:
ADD     $val1, $arg1, $arg2
ADD     $val1, $val1, $arg3
RETURN  $ra
```

Implementing procedure calls



Do we CALL/RETURN?

Store PC+1 in register (for CALL)

Load PC from register (for RETURN)

Summary

- We allow store and load of PC
- Increment to return to instruction *after* call
- Contract (calling convention) between caller and callee

(Trick) questions

- How can we compute the PC at a given instruction?
- Can we implement a dispatch table? (function pointer)
- Can a procedure call another procedure?
- What about recursion?

Conclusion

- We built a general purpose processor
- In incremental steps

Advanced tricks

- Asynchronous design
  No clock
- Caching
  Fast small memory on top of slow big memory
- Register stacks
  Accelerated procedure calls
- Floating point arithmetic, multimedia, encryption
  Upgrade the ALU
- Very large instruction word (VLIW)
  Multiple independent ALUs
- Pipelining
  Execute multiple (sub-)instructions simultaneously
- Multi-core/processor
  Multiple processors attached to a single main memory