

Computer Architecture

Robert Keller
November 2012

Computer Architecture

- A computer is essentially a large collection of **finite-state machines**.
- A common clock is used for all.
- The machines intercommunicate by the output of one machine being the input to another.
- Combinational logic can be interposed between output and input to affect data transformations.

Computer Architecture

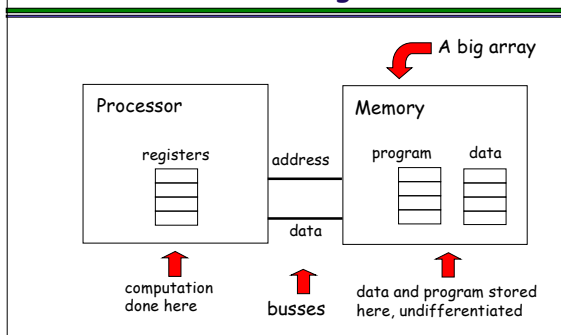
- We will work with a simulated tutorial architecture:

ISC: Incredibly Simple Computer

The ISC

- ISC is an example of a
RISC (Reduced Instruction Set Computer),
as opposed to a
CISC (Complex Instruction Set Computer)

ISC Design



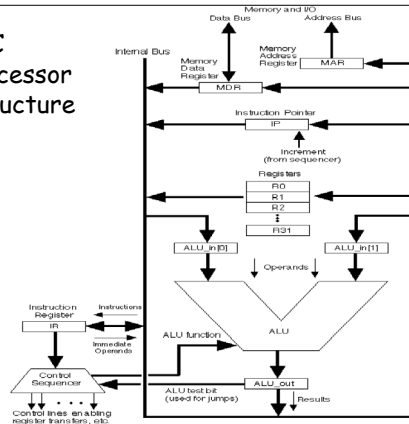
ISC Processor Components (1)

- **General Registers**: Hold operands and results, and addresses for jumps in program.
- **IR (Instruction Register)** holds currently executing instruction.
- **IP (Instruction Pointer)**: Holds address of next instruction.
- **MDR (Memory Data Register)** holds data en-route to/from memory.
- **MAR (Memory Address Register)** holds address of memory location for data.

ISC Processor Components (2)

- **ALU (Arithmetic-Logic Unit)** Combinational unit performing addition, subtraction, logical operations, shifting, etc.
- **ALU registers:** Registers holding operands and results for ALU
- **Control sequencer:** Finite-state machine sequencing register and 3-state strobes, based upon the contents of the IR (Instruction Register)

ISC Processor Structure



Instruction Dichotomies

- Instructions that access memory ("memory access" instructions)
- Instructions that include an operand in the instruction itself ("immediate" instructions)
- Instructions that change instruction location ("jump" instructions)

Non-memory access instructions

`add Ra Rb Rc`
 register indices
 (absolute or symbolic)

$reg[Ra] = reg[Rb] + reg[Rc];$

similarly for:
 sub
 mul
 div
 and
 or
 comp
 shr
 shl

"Immediate" instructions

load immediate:
`lim Ra C`

→ $Reg[Ra] = C;$

C is a constant

It can be intended for arithmetic, logic, or as an address.

add immediate:
`aim Ra C`
 $Reg[Ra] += C;$

Memory access instructions

load:
`load Ra Rb`
 → $reg[Ra] = mem[reg[Rb]];$

The address to be used is in one of the general registers.

store:
`store Ra Rb`
 → $mem[reg[Ra]] = reg[Rb];$

Jump instructions

jump-if-equal:

jeq Ra Rb Rc

→ Jump to address in Ra
if reg[Rb] == reg[Rc]

Similarly for:
jne jlt
jgt jlte
jgte

The address to be jumped to is in one of the general registers.

Jump instructions

jump-unconditionally

junc Ra

→ Jump to address in Ra.

The address to be jumped to is in one of the general registers.

Jump instructions

jump-to-subroutine

jsub Ra Rb

→ Jump to address in Ra.
The next location after the current one is put in Rb.

The address to be jumped to is in one of the general registers.

Control Sequencer FSM

- Inputs are bits from instruction being interpreted
- Outputs are strobes to various registers, 3-state devices, etc.

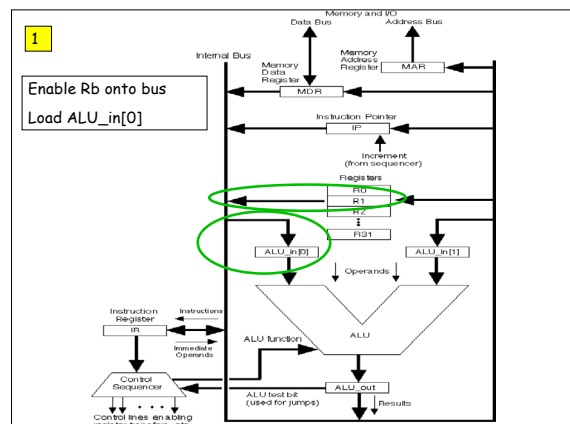
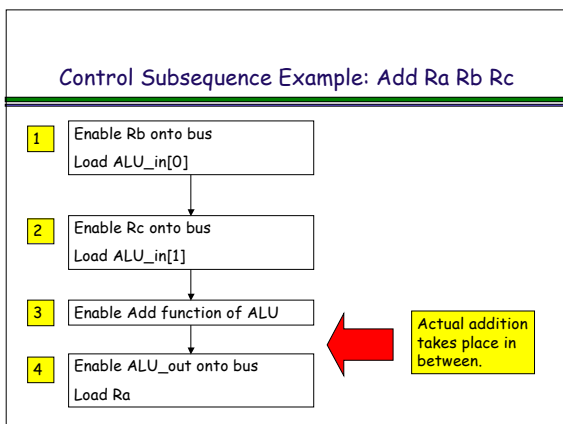
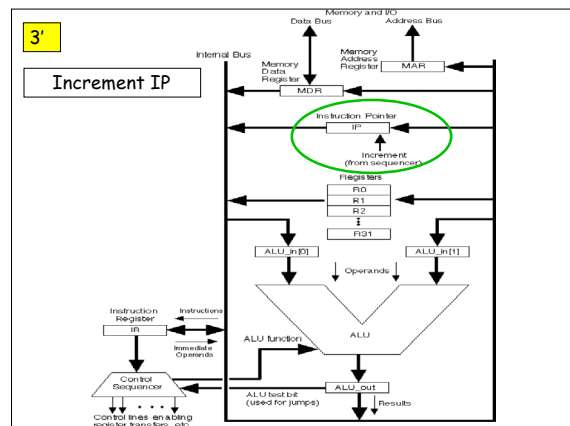
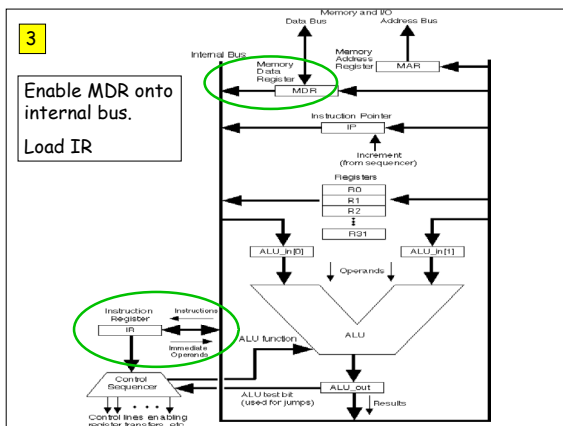
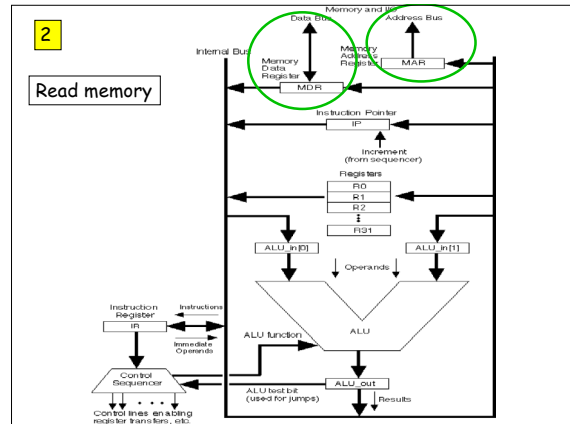
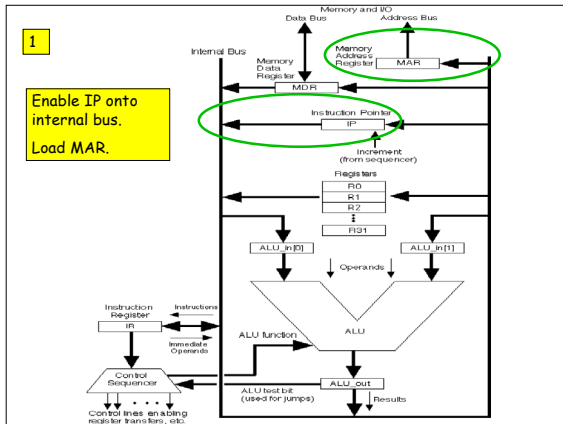
Control Sequence

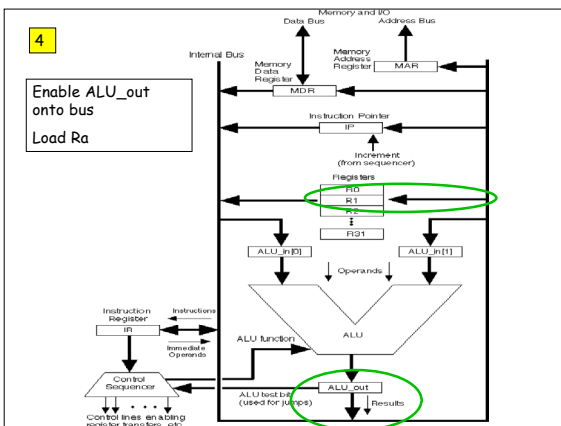
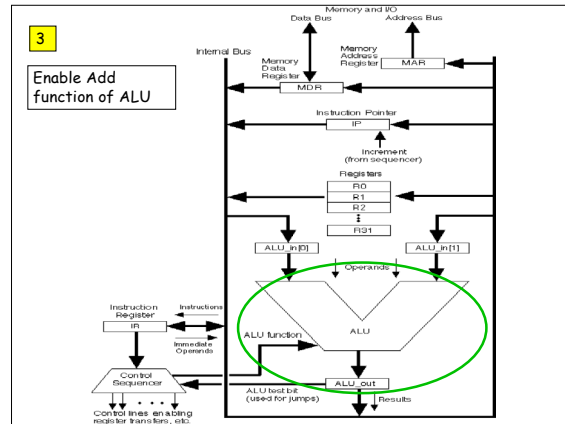
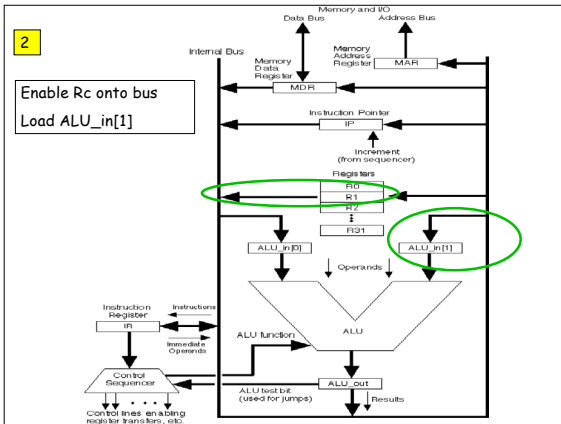
- There is a sequence common to all instructions in which the instruction is fetched from memory,
followed by
- A sequence particular to the type of instruction being executed.

ISC Instruction Fetch

```

graph TD
    1[1 Enable IP onto internal bus.  
Load MAR.] --> 2[2 Read memory]
    2 --> 3[3 Enable MDR onto internal bus.  
Load IR]
    2 --> IP[Increment IP]
    3 --> Out[ ]
    IP --> Out
    Out --> Branch[Branch to control sub-sequence based upon IR contents.]
  
```





Exercise

- What would the instruction subsequences be for:
 - aim (add immediate)
 - load
 - store
 - jeq (jump-if-equal)


Machine-Level Programming

- Programming of the bare machine is typically done in "assembly language"
- One line of assembly language is roughly equal to one machine instruction
- A program, the "assembler", allows use of symbolic identifiers for addresses.

Programming in Assembly Language

- Programming in assembly language reminds me of the Japanese saying about climbing Mt. Fuji:

"To never have climbed Mt. Fuji is to be a fool. Only a (bigger) fool would climb Mt. Fuji more than once."



ISCAL ISC Assembly Language

- See <http://www.cs.hmc.edu/~keller/isc/>
- Free-form input, but generally format line-by-line
- Regular instructions
 - *Ra, Rb, Rc* are register names
 - *C* is a constant
 - `lim Ra C`
 - `add Ra Rb Rc`
 - `copy Ra Rb`
 - `shl Ra Rb`
 - `load Ra Rb`
 - etc.

ISCAL

- Assembler directives: not instructions to computer, but rather tell assembler what to do:
 - `define Identifier Value` Defines *Identifier* to have *Value*.
 - `use Identifier` Defines *Identifier* to name an unused register.
 - `origin Value` Begin loading instructions at specified memory location. The location counter is incremented as loading progresses.
 - `label Identifier` Associates current instruction location with *Identifier*.

ISCAL code for summing an array

```

use array use count // array base and count
use sum use zero use value // local registers
use loop use done // address registers

... insert code to load array and count values ...

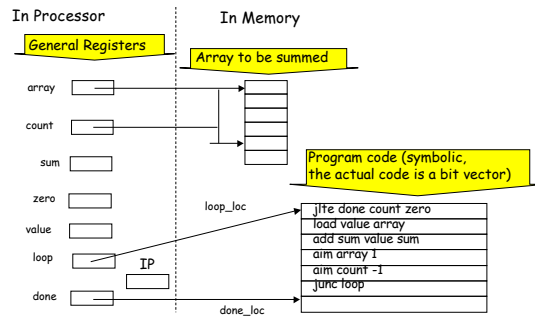
lim sum 0 // initialize sum
lim zero 0 // comparison value
lim done done_loc // address of instruction following
lim loop loop_loc // address of next instruction

label loop_loc

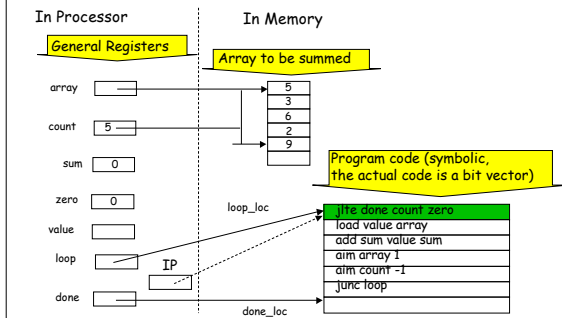
jlte done count zero // jump if <= 0
load value array // load register next array value
add sum value sum // add the next number to the sum
aim array 1 // add 1 to the array address
aim count -1 // add -1 to the count
junc loop // go back and compare

label done_loc
    
```

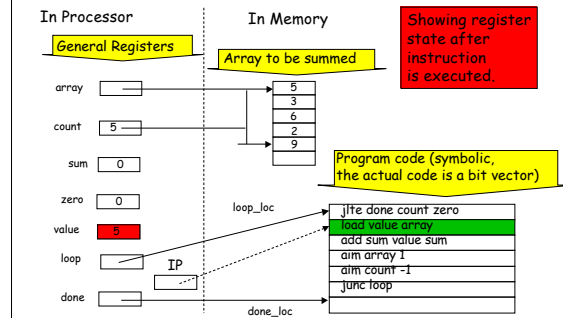
Array Summation



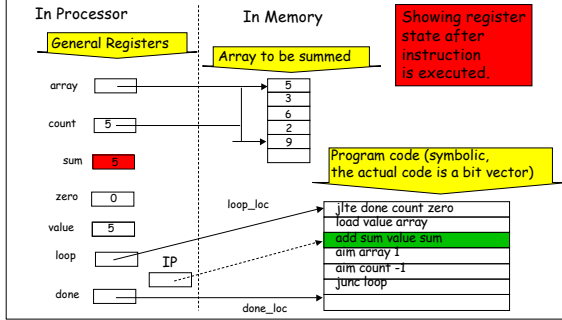
Array Summation



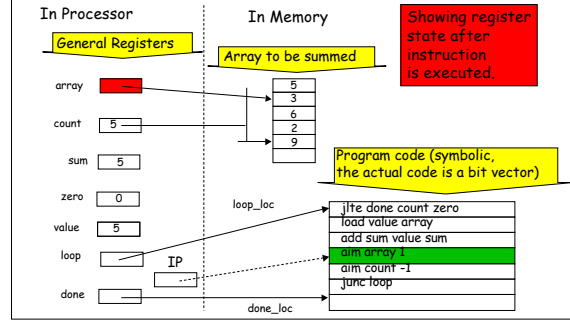
Array Summation



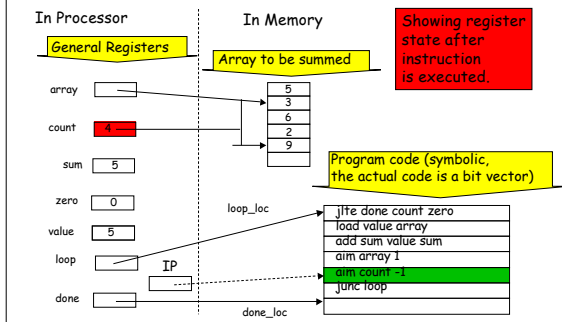
Array Summation



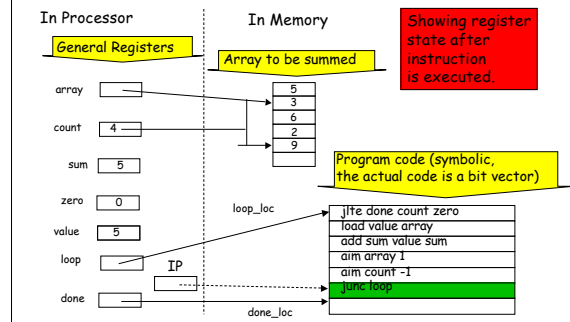
Array Summation



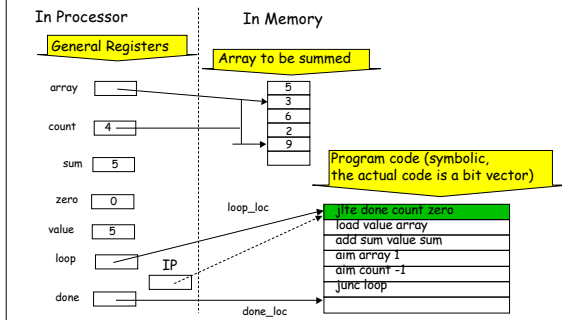
Array Summation



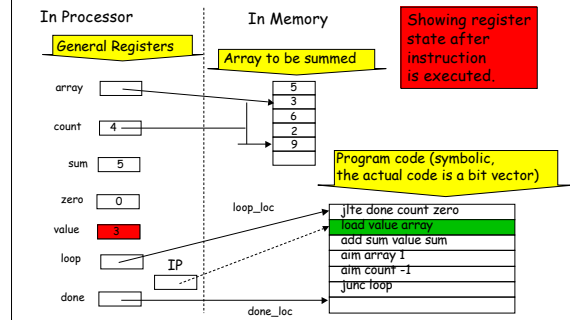
Array Summation



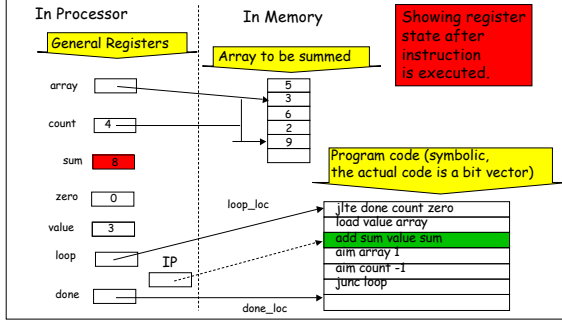
Array Summation



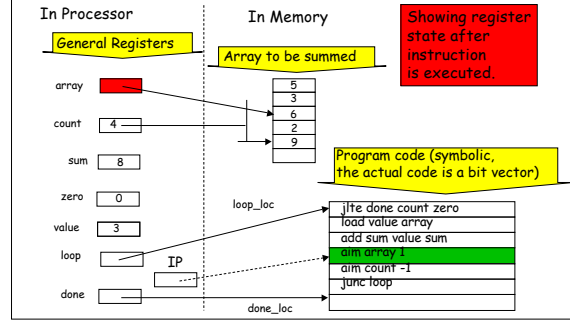
Array Summation



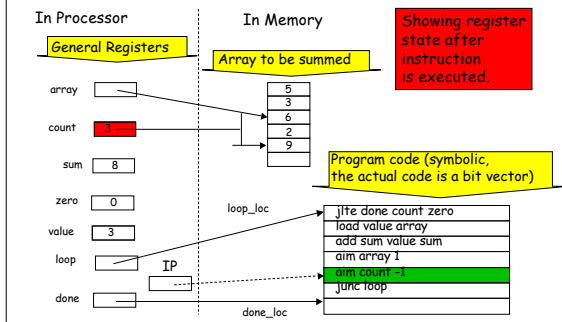
Array Summation



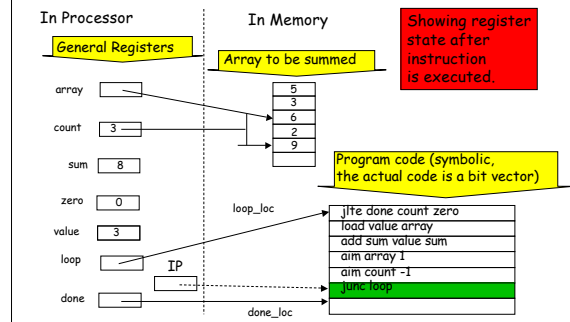
Array Summation



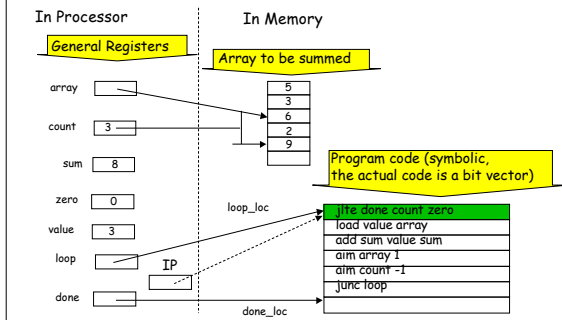
Array Summation



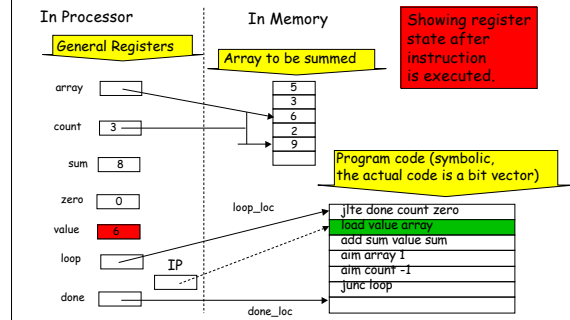
Array Summation



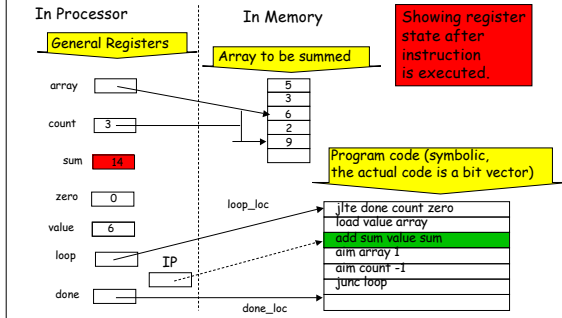
Array Summation



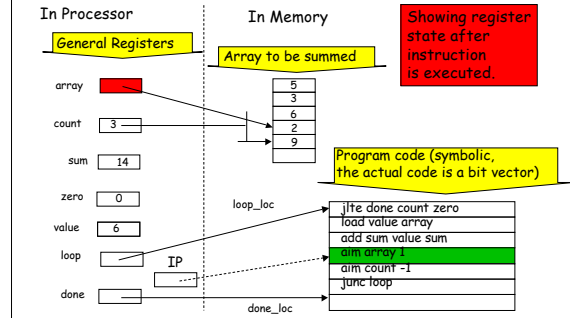
Array Summation



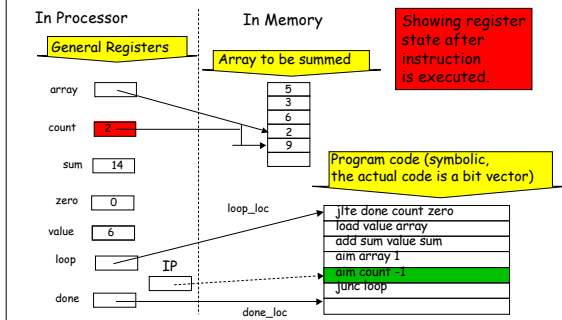
Array Summation



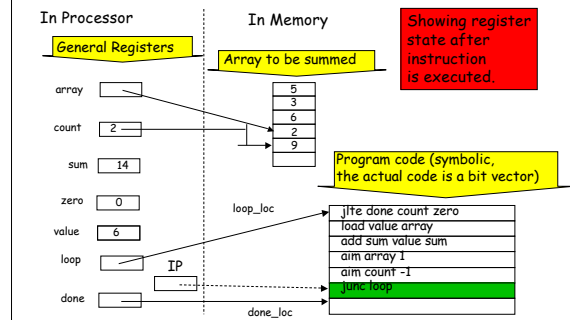
Array Summation



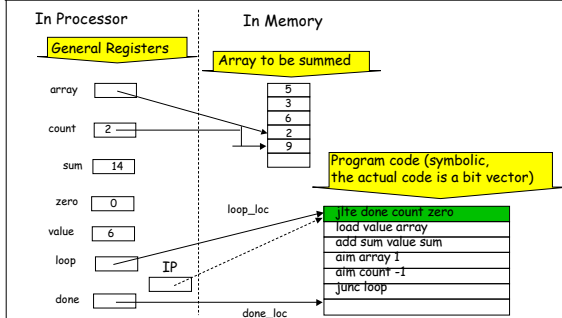
Array Summation



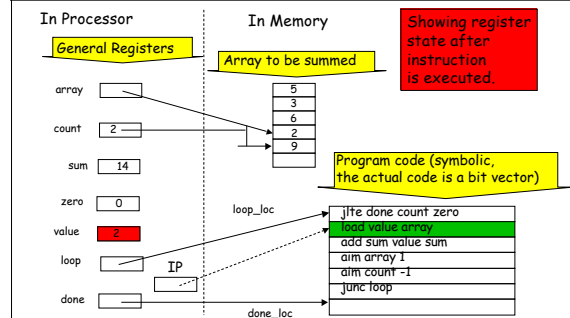
Array Summation



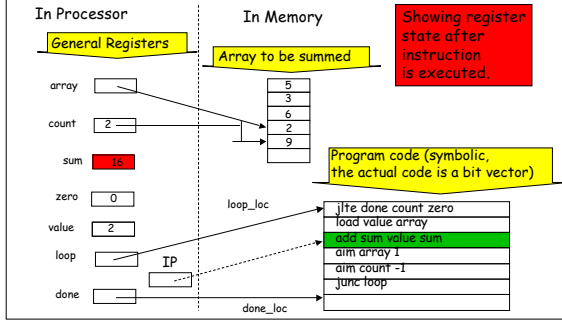
Array Summation



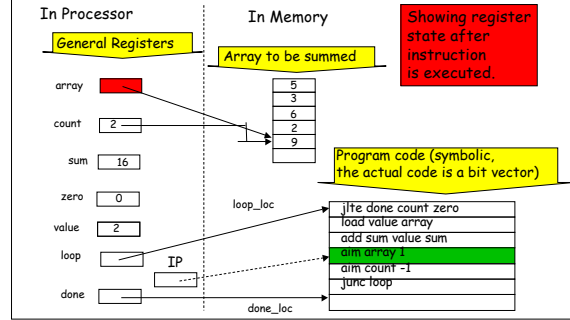
Array Summation



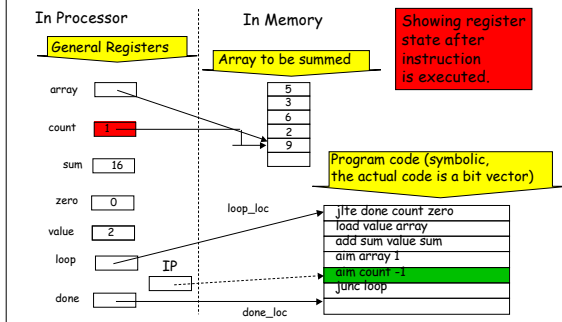
Array Summation



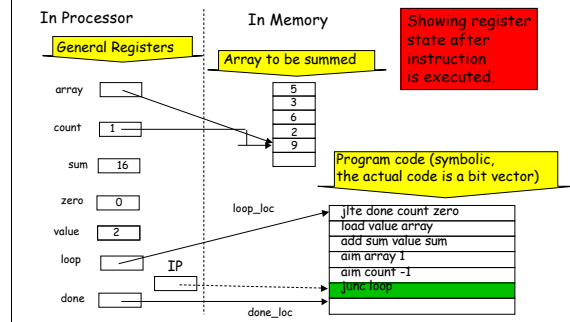
Array Summation



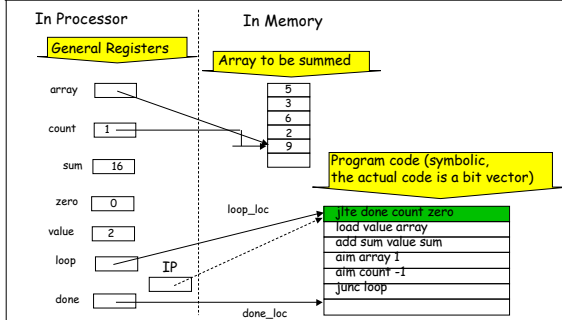
Array Summation



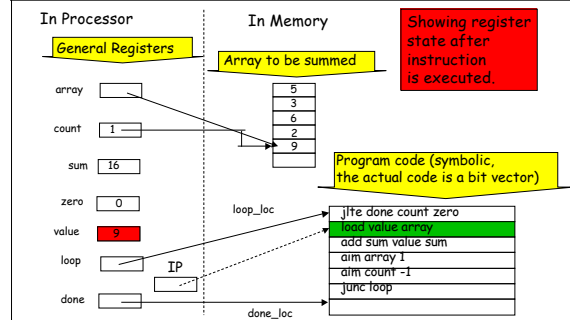
Array Summation



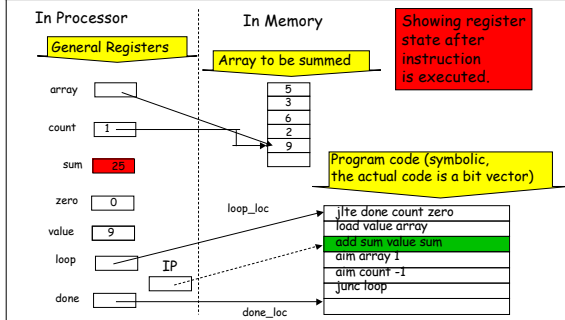
Array Summation



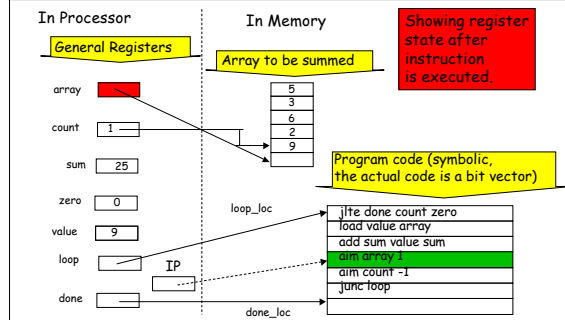
Array Summation



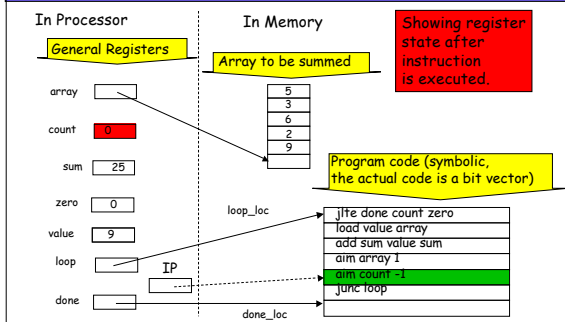
Array Summation



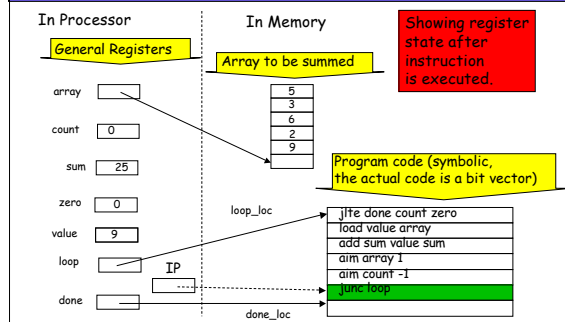
Array Summation



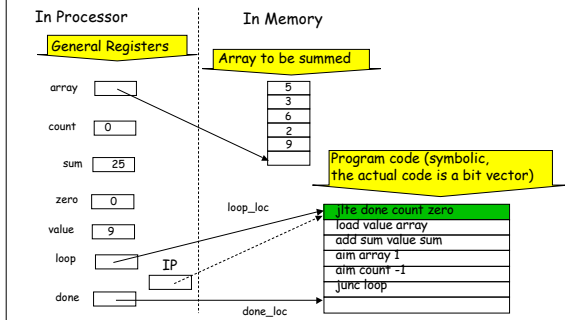
Array Summation



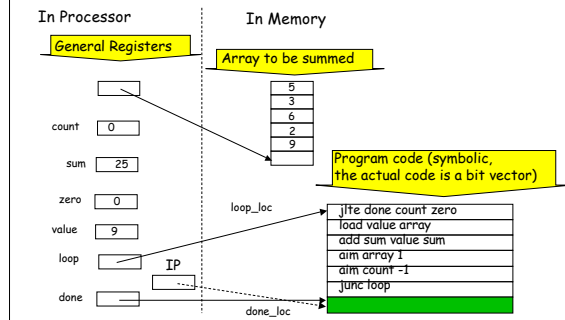
Array Summation



Array Summation



Array Summation



The ISC Assembler

- The ISC assembler is actually a combined assembler, loader, and tracer (for debugging).
- The executable is:
/cs/cs60/bin/isc
- Sample programs are in
/cs/cs60/isc/

The ISC Assembler

- The array summation program is in /cs/cs60/isc/array.isc. It includes additional code to create the array and output the result.

isc output

```
turing isc:1> isc array.isc
25
turing isc:2> isc -t array.isc
Begin trace
line: 36 loc: 0 contents: lim r9 (0) 0
reg[9] = 0
. . . lots of trace output . . .
----- output -----
25
-----
line: 88 loc: 32 contents: junc r9 (0)
jumping unconditionally to 0
```

trace flag

Implementing Procedures

- A **procedure** is just some fixed code we jump to to perform some computation.
- We put the **arguments** to the procedure into pre-agreed **standard registers**, and get the result from another register.
- The **jsub** instruction can be used to get the **return address**.

Implementing Recursion

- Recursion presents a problem: The fixed code would tend to clobber (an inelegant way of saying "over-write") the return address when the procedure calls itself.
- Also, the arguments in registers would get clobbered.

Stacks to the Rescue

- To deal with the clobbering problem, we can **save** the return address and any arguments on a **stack** allocated at a standard place in memory.
- The stack is typically an array, with a pointer to the top element.

```
lim stack_pointer save_area_loc // initialize stack pointer
aim stack_pointer -1 // always point to top of stack
```

Example: Recursive Factorial

```
label fac // recursive factorial routine
lim result 1 // basis is 1
jlte return arg zero // return if count is 0 or less

push aim stack_pointer +1 // increment stack pointer
store stack_pointer return // save return address on stack

push aim stack_pointer +1 // increment stack pointer
store stack_pointer arg // save argument on stack

aim arg -1 // subtract 1 from argument
jsub jump_target return // call recursively

pop load arg stack_pointer // restore original argument
aim stack_pointer -1

pop load return stack_pointer // restore original return address
aim stack_pointer -1

mul result result arg // multiply by original arg
junc return // return to caller
```

Stack trace of factorial(4)

Stack trace of factorial(4)