IBCM

C++ to assembly to machine code

hello.cpp

```
#include <iostream>
int main() {
  std::cout << "Hello!\n";
  return 0;
}
```

hello.o (not shown)

C++ to assembly to machine code

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```
#include <iostream>
int main() {
  std::cout << "Hello!\n";
  return 0;
}
```

hello.s

```
.LC0:
  .string "Hello!\n"
main:
  sub rsp, 8
  mov esi, .LC0         # arg1 ← "Hello!\n"
  mov edi, _ZSt4cout    # arg2 ← cout
  call _ZStlsISt11char_traitsIcEERSt13basic_ostreamIcT_ES5_P
                        # call operator<<
  xor eax, eax          # return value ← 0
  pop rdx
  ret                   # return
```

hello.o (not shown)

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                         # call operator<<
  xor eax, eax           # return value ← 0
  pop rdx
  ret                    # return
```

hello.o (not shown)

+ standard library

hello.exe

(actually binary bytes without comments,
but shown as hexadecimal bytes with comments)

```
…
48 83 ec 08       # sub rsp, 8
be 64 07 40 00    # mov esi, .LC0 == 0x400764
bf 60 10 60 00    # mov edi, _ZSt4cout == 0x601060
e8 bd ff ff ff    # call operator<<
31 c0             # xor eax, eax
5a                # pop rdx
c3                # ret
…
```

assembly language and machine language

machine language — what the physical hardware expects
   how it reads bytes of memories when looking for work

assembly language — text representation of that
   direct translation to machine code

why learn assembly?

designing hardware

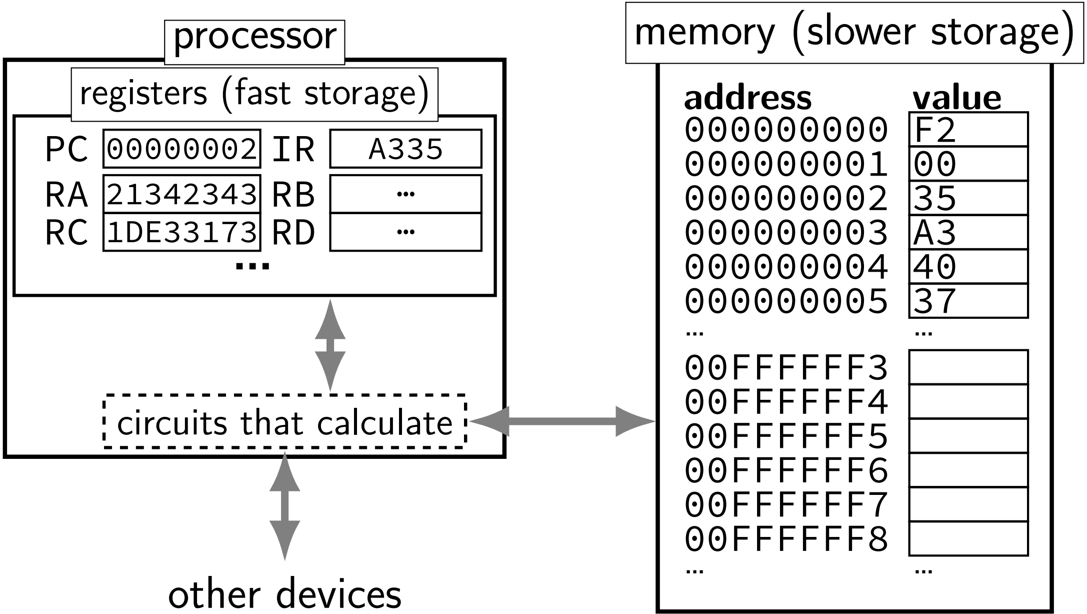
writing compilers

writing operating systems

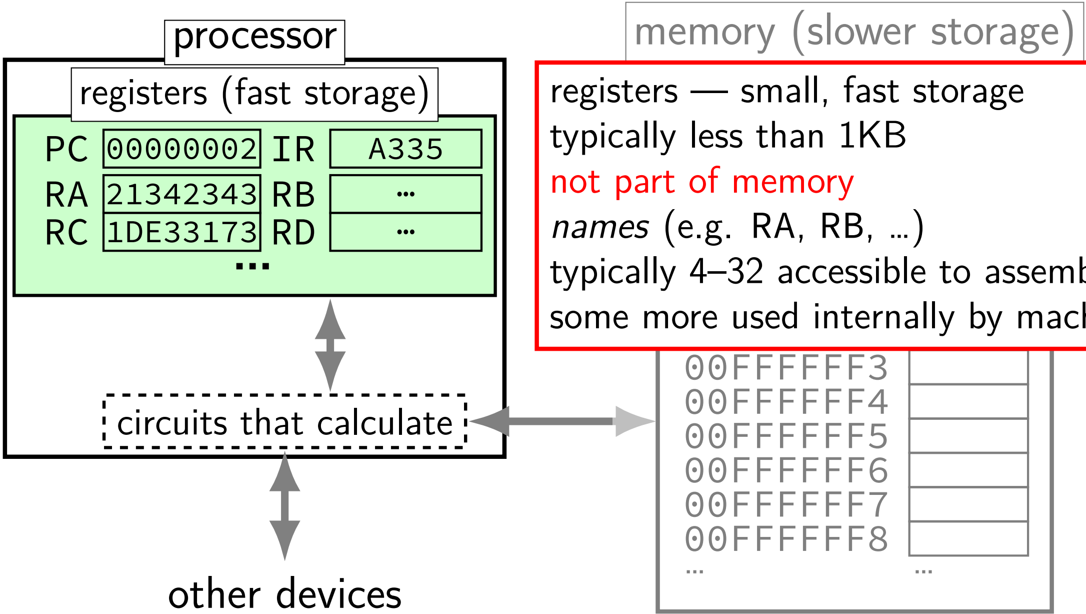
understanding how compilers work

understanding how computers work

our machine model

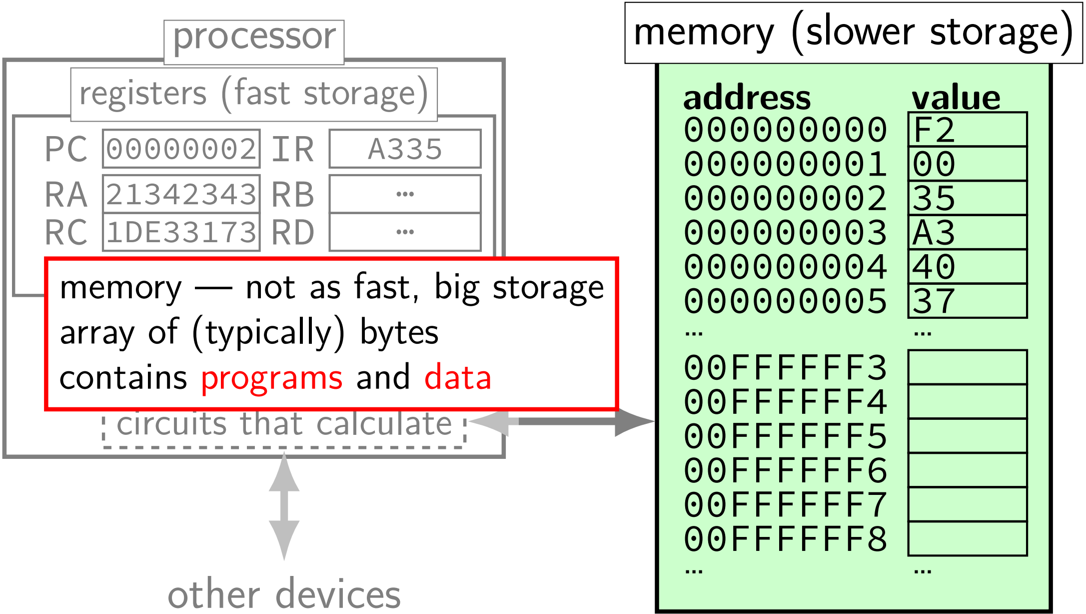


our machine model



registers — small, fast storage
typically less than 1KB
not part of memory
names (e.g. RA, RB, …)
typically 4–32 accessible to assembly
some more used internally by machine

our machine model



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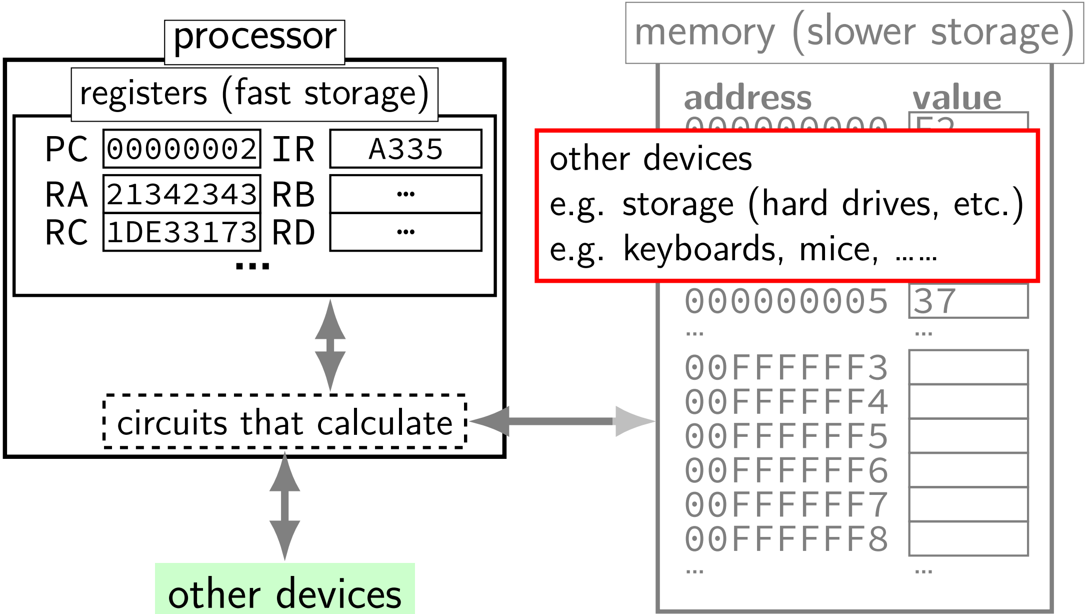

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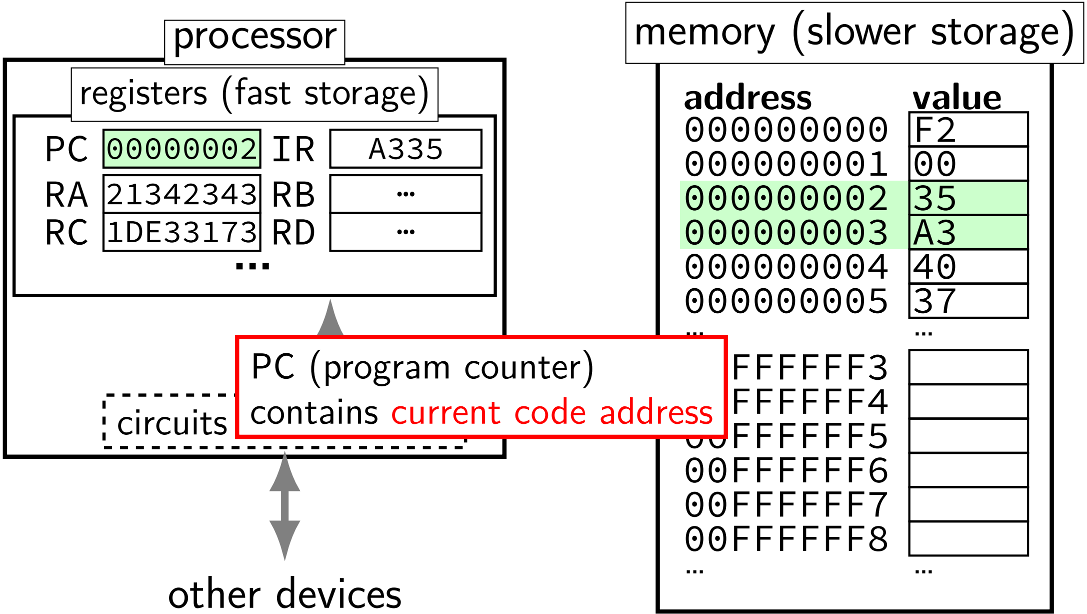
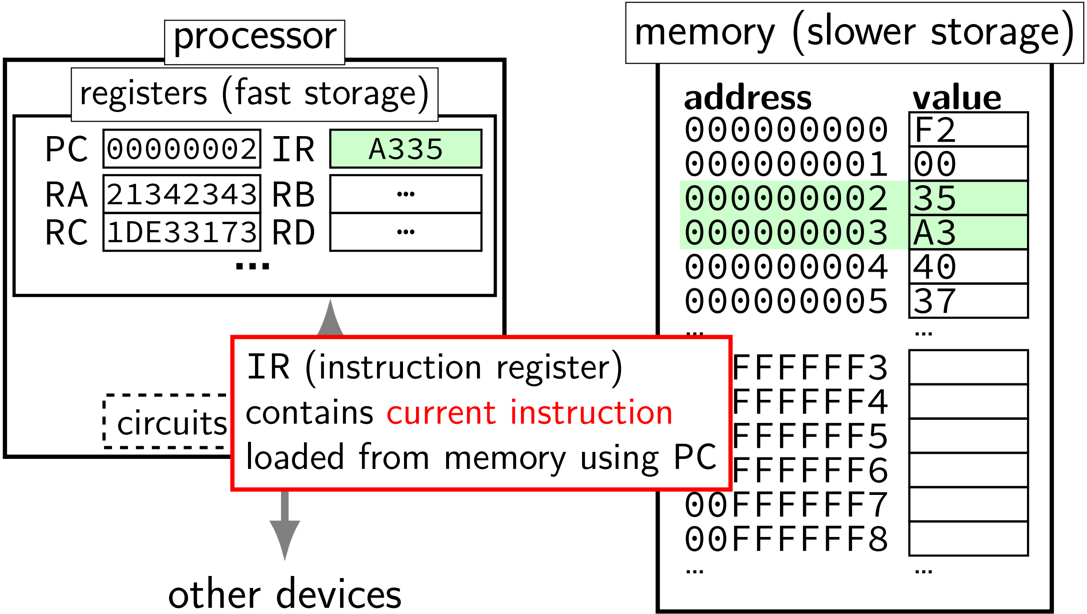


our machine model



fetch execute cycle

```
while (true) {
    IR <- memory[PC]
    execute instruction IR
    if (instruction didn't change PC)
        PC <- PC + length of instruction in IR
}
```

PC = program counter

IR = instruction register

instructions — one operation

in machine code: represented by bits

in assembly language: reprsented by text

example instructions

(in assembly language)

x86 example:

```
add ecx, ebx
add ecx, 1
```

(ecx and ebx are registers)

IBCM example:

```
load 100
add 200
store 300
```

(implicitly uses special “accumulator” register)

IBCM simulators

toy assembly language **IBCM**

no physical implementation, so...

simulators (all point to same implementation):

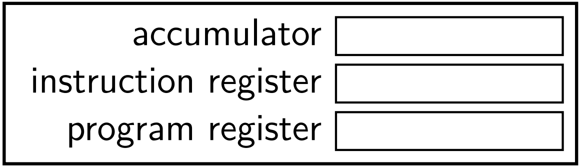
    https://www.cs.virginia.edu/~cs216/ibcm/
    https://people.virginia.edu/~asb2t/ibcm/

works in browser

will do bad things if your program doesn't terminate

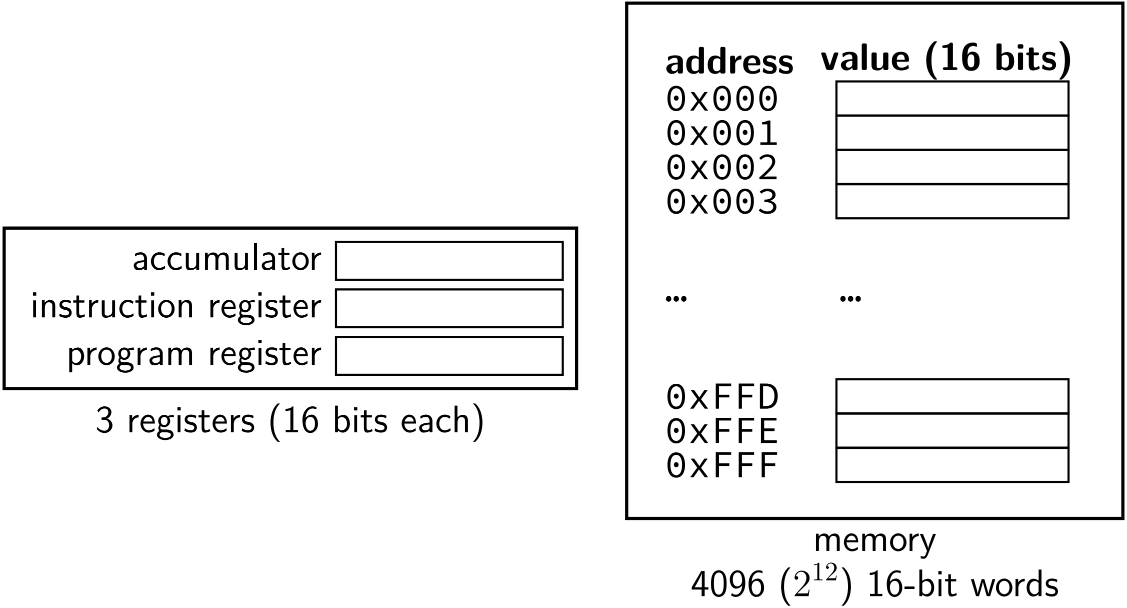
(turn off the simulated machine)

IBCM machine state



3 registers (16 bits each)

IBCM machine state



on words

we deal with a lot of 16-bit values

"natural" size of this machine

- size of registers
- size of memory accesses
- ...

convention: natural size called word

IBCM: *only* size for registers

IBCM: size of instructions in machine code

IBCM instruction format

<table>
<tr><th>15</th><th>14</th><th>13</th><th>12</th><th>11</th><th>10</th><th>9</th><th>8</th><th>7</th><th>6</th><th>5</th><th>4</th><th>3</th><th>2</th><th>1</th><th>0</th><th></th></tr>
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opcode

which instruction?

IBCM instruction format

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`halt` — opcode `0`
stops the machine

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I/O operation – opcode 1
4 types (“I/O op” bits)
into or out of *accumulator*

IBCM instruction format

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0	
0	0	0	0													
0	0	0	1	*I/O op*												
0	0	1	0	*shift op*												
opcode				*address*												others

I/O op	name	effect
00	`readH`	read hex word
01	`readC`	read ASCII character (into accumulator bits 0–7)
10	`printH`	write hex word
11	`printC`	write ASCII charcater (from accumulator bits 0–7)

IBCM instruction format

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`shift` — opcode 2

4 types (“shift op”) move bits of accumulator around

count is number of places to move

shifts

has *shift op* (2 bits) and *count* (3 bits)

example: accumulator=`0000 1111 0000 1111`; *count*=3

shift op	desc.	name	example result
`00`	shift left	`shiftL`	`0111 1000 0111 1000`
`01`	shift right	`shiftR`	`0000 0001 1110 0001`
`10`	rotate left	`rotL`	`0111 1000 0111 1000`
`11`	rotate right	`rotR`	`1110 0001 1110 0001`

shift: move bits, fill with `0`s

rotate: move bits, wrap around

other instructions

use accumulator (a or “acc”) and/or address *in instruction*

op	*name*	*pseudocode*	*description*
3	`load`	`a` ← `mem[addr]`	load acc from memory
4	`store`	`mem[addr]` ← `a`	store acc to memory
5	`add`	`a` ← `a + mem[addr]`	add memory to acc
6	`sub`	`a` ← `a + mem[addr]`	subtract mememory from acc
7	`and`	`a` ← `a` ∧ `mem[addr]`	logical ‘and’ memory into acc
8	`or`	`a` ← `a` ∨ `mem[addr]`	logical ‘or’ memory into acc
9	`xor`	`a` ← `a` ⊕ `mem[addr]`	logical ‘xor’ memory into acc
A	`not`	`a` ← `~a`	logical complement acc
B	`nop`	—	do nothing (‘no operation’)
C	`jmp`	`PC` ← `addr`	jump to `addr`
D	`jmpe`	`if a == 0: PC` ← `addr`	jump to `addr` if acc is 0
E	`jmpl`	`if a < 0: PC` ← `addr`	jump to `addr` if acc is negative
F	`brl`	`a` ← `PC + 1; PC` ← `addr`	jump to `addr` and set acc to the address following the `brl`

brl

"**br**anch and **l**ink"

`a ← PC + 1; PC ← addr`

used to implement method calls:

example: `addr` is the address of a method

a becomes the `return address`

- instruction to execute *after the method returns*
- issue in IBCM: jumping to a???

ICBM assembly language

don't have an assembler implemented

...but let's see what an assembly language would look like

ICBM assembler

assembly: `load 0x100`
→ opcode=3, addr=`0x100`
machine code: `0011 000100000000`

assembly: `add 0x200`
→ opcode=5, addr=`200`
machine code: `0101 001000000000`

assembly: `jmpe 0x442`
→ opcode=D, addr=`442`
machine code: `1101 010001000010`

ICBM assembler

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assembly: `jmpe 0x442`
→ opcode=D, addr=`442`
machine code: `1101 010001000010`

work with hard-coded addresses?
how to set initial values?

labels: addresses as names

```
add     100     // addr 0: a += mem[100]
jmpl    3       // addr 1: if a < 0: goto 3
jmp     0       // addr 2: [otherwise] goto 0
nop             // addr 3: do nothing
```

labels: addresses as names

```
add     100     // addr 0: a += mem[100]
jmpl    3       // addr 1: if a < 0: goto 3
jmp     0       // addr 2: [otherwise] goto 0
nop             // addr 3: do nothing
```

```
start  add    100      // addr 0: a += mem[100]
       jmpl   end      // addr 1: if a < 0: goto 3
       jmp    start    // addr 2: [otherwise] goto 0
end    nop             // addr 3: do nothing
```

labels: addresses as name

```
start   add     100     // addr 0: a += mem[100]
        jmpl    end     // addr 1: if a < 0: goto 3
        jmp     start   // addr 2: [otherwise] goto 0
end     nop             // addr 3: do nothing
```

name for a memory address

address of instruction or of data

replaced by address when executable is produced

ICBM assembler

assembly: `load` `0x100`
→ opcode=3, addr=`0x100`
machine code: `0011 000100000000`

assembly: `add` `0x200`
→ opcode=5, addr=`200`
machine code: `0101 001000000000`

assembly: `jmpe` `0x442`
→ opcode=D, addr=`442`
machine code: `1101 010001000010`

work with hard-coded addresses?
how to set initial values?

assembly directives

not everything in assembly is instructions

program data, strings, etc.

assemblers have directives

processed by assembler to produce special output

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assemblers have directives

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dw directive (“define word”)

assembly directives

not everything in assembly is instructions

program data, strings, etc.

assemblers have directives

processed by assembler to produce special output

dw directive ("define word")

`i dw 75`

place the value 75 in memory
name the address where it is placed `i`

example with dw

```
        load hundred    // a ← 100
loop    jmpl end        // if a < 0: goto end
        printH          // print a
        sub one         // a ← a - 1
        jmp loop
end     halt

hundred dw 100
one     dw 1
```

```
int a = 100;
while (a >= 0) {
    print a;
    a -= 1;
}
```

variables with dw

```
          load i
          add j
          store i

          load j
          sub i
          sub i
          store j

i         dw 10
j         dw 20
```

```
int i = 10, j = 20;
i += j;
j -= i;
j -= i;
```

IBCM format

our simulators: first four characters of each line only

example of suggested format:

```
mem  locn label op       addr    comments
C00A 000        jmp       start   skip around the vars
0000 001   i    dw        0       int i
0000 002   s    dw        0       int s
0000 003   a    dw        0       int a[]
0000 004   n    dw        0
0000 005   zero dw        0
0001 006   one  dw        1
5000 007   adit dw        5000
...                              leave space for changes
1000 00A   start readH            read array addres
```

leaving room for changes

insert blank space for:

- extra variable/constant declaratoins
- maybe extra instructions in loops?

to make changes easier

IBCM decoding

value
0000
000f
0005
3041
5002
1800
2403
0000

IBCM decoding

value
`0000`
`000f`
`0005`
`3041`
`5002`
`1800`
`2403`
`0000`

most significant 4 bits = opcode

0 — halt

1 — some kind of I/O

3 — load

5 — add

IBCM decoding

value	as instruction
`0000`	`halt`
`000f`	`halt`
`0005`	`halt`
`3041`	`load ?`
`5002`	`add ?`
`1800`	`?? I/O`
`2403`	`?? shift`
`0000`	`halt`

most significant 4 bits = opcode

`0` — halt

1 — some kind of I/O

3 — load

5 — add

IBCM decoding

value	as instruction
`0000`	`halt`
`000f`	`halt`
`0005`	`halt`
`3041`	`load ?`
`5002`	`add ?`
`1800`	`?? I/O`
`2403`	`?? shift`
`0000`	`halt`

halt — rest of instruction ignored

IBCM decoding

value	as instruction
`0000`	`halt`
`000f`	`halt`
`0005`	`halt`
`3041`	`load 0x41`
`5002`	`add 0x2`
`1800`	`?? I/O`
`2403`	`?? shift`
`0000`	`halt`

load/add — rest is address

IBCM decoding

value	as instruction
`0000`	`halt`
`000f`	`halt`
`0005`	`halt`
`3041`	`load 0x41`
`5002`	`add 0x2`
`1800`	`printH`
`2403`	`shiftR ?`
`0000`	`halt`

I/O: bits 10–11 $=$ `10` $\rightarrow$ `printH`

shift: bits 10–11 $=$ `01` $\rightarrow$ `shiftR`

IBCM decoding

value	as instruction
`0000`	`halt`
`000f`	`halt`
`0005`	`halt`
`3041`	`load 0x41`
`5002`	`add 0x2`
`1800`	`printH`
`2403`	`shiftR 3`
`0000`	`halt`

shift amount in bottom 4 bits

IBCM sample program

addr.	value
000	3000
001	5000
002	6001
003	8003
004	a000
005	4000
006	f000

PC 000

IR ????

accumulator 3000

IBCM sample program

addr.	value	as instruction
000	3000	load 0
001	5000	add 0
002	6001	sub 1
003	8003	or 3
004	a000	not
005	4000	store 0
006	f000	brl 0

PC	000
IR	3000
accumulator	3000

accumulator $\leftarrow$ `0x3000` $=$ memory[0]

IBCM sample program

addr.	value	as instruction
000	3000	load 0
001	5000	add 0
002	6001	sub 1
003	8003	or 3
004	a000	not
005	4000	store 0
006	f000	brl 0

PC	001
IR	3000
accumulator	3000

IBCM sample program

addr.	value	as instruction
000	3000	load 0
001	5000	add 0
002	6001	sub 1
003	8003	or 3
004	a000	not
005	4000	store 0
006	f000	brl 0

PC 001

IR 5000

accumulator 6000

accumulator $\leftarrow$ `0x6000` $=$ `0x3000` $+$ memory[0]

IBCM sample program

addr.	value	as instruction
000	3000	load 0
001	5000	add 0
002	6001	sub 1
003	8003	or 3
004	a000	not
005	4000	store 0
006	f000	brl 0

PC 002

IR 6001

accumulator 5000

accumulator $\leftarrow$ 0x1000 $=$ 0x6000 - memory[1]

IBCM sample program

addr.	value	as instruction
`000`	`3000`	`load 0`
`001`	`5000`	`add 0`
`002`	`6001`	`sub 1`
`003`	`8003`	`or 3`
`004`	`a000`	`not`
`005`	`4000`	`store 0`
`006`	`f000`	`brl 0`

PC `003`

IR `8003`

accumulator `9003`

accumulator ← `0x9003` = `0x1000` OR memory[3]

"or" — bitwise or:
bit x set in result if set in either operand

IBCM sample program

addr.	value	as instruction
000	3000	load 0
001	5000	add 0
002	6001	sub 1
003	8003	or 3
004	a000	not
005	4000	store 0
006	f000	brl 0

PC	004
IR	a000
accumulator	6ffc

accumulator $\leftarrow$ `0x6ffc` = NOT 0x9003

"not" — flip every bit

IBCM sample program

addr.	value	as instruction
000	6ffc	~~load 0~~sub FFC
001	5000	add 0
002	6001	sub 1
003	8003	or 3
004	a000	not
005	4000	store 0
006	f000	brl 0

PC $\boxed{005}$

IR $\boxed{4000}$

accumulator $\boxed{6ffc}$

memory[0] $\leftarrow$ accumulator

IBCM sample program

addr.	value	as instruction
000	6ffc	~~load 0~~sub FFC
001	5000	add 0
002	6001	sub 1
003	8003	or 3
004	a000	not
005	4000	store 0
006	f000	brl 0

PC 006

IR f000

accumulator 0007

$$\text{accumulator} \leftarrow \text{PC} + 1\text{PC} \leftarrow 0$$

IBCM sample program

addr.	value	as instruction
000	6ffc	~~load 0~~sub FFC
001	5000	add 0
002	6001	sub 1
003	8003	or 3
004	a000	not
005	4000	store 0
006	f000	brl 0

PC 001

IR 6ffc

accumulator ????

accumulator ← ??? = 0x0007 - memory[0xFFC]

example: if/else

```
if (B == 0)
    S1;
else
    S2;
S3;
```

example: if/else

```
if (B == 0)
    S1;
else
    S2;
S3;
```

```
load B
jmpe S1
jmp S2
```

jmpe — jump if acc. zero

example: if/else

```
if (B == 0)
    S1;
else
    S2;
S3;
```

```
        load B
        jmpe S1
        jmp S2
S1      (S1's code)
        jmp S3
```

jmpe — jump if acc. zero

skip over S2 after S1

example: if/else

```
if (B == 0)
     S1;
else
     S2;
S3;
```

```
        load B
        jmpe S1
        jmp S2
S1      (S1's code)
        jmp S3
S2      (S2's code)
S3      (S3's code)
```

jmpe — jump if acc. zero

skip over S2 after S1

can omit jump to S3,
since it's right after

example: while

```
while (B >= 5)
    S1;
S2;
```

example: while

```
while (B >= 5)
      S1;
S2;
```

```
        jmp loop
five    dw 5
loop    load B
        sub five
        jmpl S2
```

need constant '5'

B - 5 $< 0 \rightarrow$

done with loop

example: while

```
while (B >= 5)
    S1;
S2;
```

```
      jmp loop
five  dw 5
loop  load B
      sub five
      jmpl S2
```

```
S1    (S1's code)
      jmp loop
```

need constant '5'

B - 5 $<$ 0 $\rightarrow$ done with loop

example: while

```
while (B >= 5)
    S1;
S2;
```

```
      jmp loop
five  dw 5
loop  load B
      sub five
      jmpl S2
S1    (S1's code)
      jmp loop
S2    (S2's code)
```

need constant '5'

B - 5 $<$ 0 $\rightarrow$ done with loop

example: sum

the task:

read in integer n from keyboard

compute sum of integers 1 to n (inclusive)

print sum

halt

sum psuedocode

```
read n;
i = 1;        // index in the array
s = 0;        // ongoing sum
while (i <= n) {
  s += i;
  i += 1;
}
print s;
```

translating sum (1)

```
read n;
i = 1;
s = 0;
while (i <= n) {
    s += i;
    i += 1;
}
print s;
```

translating sum (1)

```
read n;
i = 1;
s = 0;
while (i <= n) {
   s += i;
   i += 1;
}
print s;
```

```
label instr
i       dw 0
s       dw 0
n       dw 0
one     dw 1
zero    dw 0
```

allocate variables and needed constants

translating sum (1)

```
read n;
i = 1;
s = 0;
while (i <= n) {
   s += i;
   i += 1;
}
print s;
```

label	instr	
	jmp start	don't execute vars, etc.
i	dw 0	
s	dw 0	allocate variables
n	dw 0	and needed constants
one	dw 1	
zero	dw 0	
start	readH	
	store n	
	load one	load into accum.
	store i	then store in variable
	load zero	
	store s	

translating sum (1)

```
read n;
i = 1;
s = 0;
while (i <= n) {
   s += i;
   i += 1;
}
print s;
```

label	instr	
	jmp start	don't execute vars, etc.
i	dw 0	
s	dw 0	allocate variables
n	dw 0	and needed constants
one	dw 1	
zero	dw 0	
start	readH	
	store n	
	load one	load into accum.
	store i	then store in variable
	load zero	
	store s	

translating sum (2)

```
read n;
i = 1;
s = 0;
while (i <= n) {
   s += i;
   i += 1;
}
print s;
```

```
label instr
        ...
        load zero
        store s
```

allocate vars/constants
initial reads/assignment

translating sum (2)

```
read n;
i = 1;
s = 0;
while (i <= n) {
   s += i;
   i += 1;
}
print s;
```

```
label instr
      ...
      load zero
      store s
```

allocate vars/constants
initial reads/assignment

```
loop  load n
      sub i
      jmpl done
```

'done' = end of loop
if n - i < 0: goto done

```
      jmp loop
done
```

return to start of loop
label *after* end of loop

translating sum (2)

```
read n;
i = 1;
s = 0;
while (i <= n) {
   s += i;
   i += 1;
}
print s;
```

```
label instr
        ...
        load zero
        store s
loop    load n
        sub i
        jmpl done
        load s
        add i
        store s
        load i
        add one
        store i
       jmp loop
done
```

allocate vars/constants
initial reads/assignment

'done' = end of loop
if n - i < 0: goto done

return to start of loop
label *after* end of loop

translating sum (2)

```
read n;
i = 1;
s = 0;
while (i <= n) {
   s += i;
   i += 1;
}
print s;
```

label	instr	
	...	allocate vars/constants
	load zero	initial reads/assignment
	store s	
loop	load n	'done' = end of loop
	sub i	if n - i < 0: goto done
	jmpl done	
	load s	
	add i	
	store s	
	load i	
	add one	
	store i	
	jmp loop	return to start of loop
done	load s	label *after* end of loop
	printH	

example: array sum

the task:

read address a from keyboard

read size n from keyboard

compute sum of n-element array at that addres

print sum

halt

array sum psuedocode

```
read a;         // array base address
read n;         // array size
i = 0;          // index in the array
s = 0;          // ongoing sum
while (i < n) {
  s += a[i];
  i += 1;
}
print s;
```

accessing array elements?

want to add `a[i]` to something...

can compute *address of* a[i] in the accumulator:

```
load a
add i
```

...but no instruction to load address into accumulator

...or add address into accumulator ...

solution: write `add a[i]` instruction

encoding: opcode=5 rest=address of a[i]

the trick: writing instructions

```
addInst        dw 0x5000
a              dw 0x100
i              dw 0x45
...
      load     addInst   load inst. template
      add      a         address += a
      add      i         address += i
      store    doit      plant inst into the code
      load     s         accum = s
doit  dw       0         s +=  a[i]
```

0x5000 (add 0) → 0x5100 (add 0x100) → 0x5145 (add 0x145)

the trick: writing instructions

```
addInst       dw 0x5000
a             dw 0x100
i             dw 0x45
...
      load     addInst   load inst. template
      add      a         address += a
      add      i      address += i
      store    doit   plant inst into the code
      load     s      accum = s
doit  dw       0      s +=  a[i]
```

0x5000 (add 0) → 0x5100 (add 0x100) → 0x5145 (add 0x145)

the trick: writing instructions

```
addInst       dw 0x5000
a             dw 0x100
i             dw 0x45
...
      load      addInst   load inst. template
      add       a         address += a
      add       i         address += i
      store     doit      plant inst into the code
      load      s         accum = s
doit  dw        0         s += a[i]
```

0x5000 (add 0) → 0x5100 (add 0x100) → 0x5145 (add 0x145)

the trick: writing instructions

```
addInst      dw 0x5000
a            dw 0x100
i            dw 0x45
...
      load      addInst   load inst. template
      add       a         address += a
      add       i      address += i
      store     doit   plant inst into the code
      load      s      accum = s
doit  dw        0      s +=  a[i]
```

0x5000 (add 0) → 0x5100 (add 0x100) → 0x5145 (add 0x145)

the trick: writing instructions

```
addInst        dw 0x5000
a              dw 0x100
i              dw 0x45
...
      load     addInst   load inst. template
      add      a         address += a
      add      i      address += i
      store    doit   plant inst into the code
      load     s      accum = s
doit  dw       0      s +=  a[i]
```

0x5000 (add 0) → 0x5100 (add 0x100) → 0x5145 (add 0x145)

translating array sum (1)

```
read a;
read n;
i = 0;
s = 0;
while (i < n) {
   s += a[i];
   i += 1;
}
print s;
```

```
label instr comment
      jmp start
i     dw 0
s     dw 0
n     dw 0
one   dw 1
zero  dw 0
addInst  dw 5000   add inst to fill in
start readH              read array address
      store    a
      readH              read array size
      store    n
      load     zero
      store    i         i = 0
      store    s         s = 0
loop  load     n         if (i >= N) goto xit
      ...
xit   load s
      printH
      halt
```

translating array sum (1)

```
read a;
read n;
i = 0;
s = 0;
while (i < n) {
   s += a[i];
   i += 1;
}
print s;
```

```
label instr comment
      jmp start
i     dw 0
s     dw 0
n     dw 0
one   dw 1
zero  dw 0
addInst  dw 5000   add inst to fill in
start readH             read array address
      store     a
      readH             read array size
      store     n
      load      zero
      store     i       i = 0
      store     s       s = 0
loop  load      n       if (i >= N) goto xit
      ...
xit   load s
      printH
      halt
```

translating array sum (1)

```
read a;
read n;
i = 0;
s = 0;
while (i < n) {
   s += a[i];
   i += 1;
}
print s;
```

```
label instr comment
        jmp start
i       dw 0
s       dw 0
n       dw 0
one     dw 1
zero    dw 0
addInst   dw 5000    add inst to fill in
start   readH              read array address
        store     a
        readH              read array size
        store     n
        load      zero
        store     i        i = 0
        store     s        s = 0
loop    load      n        if (i >= N) goto xit
        ...
xit     load s
        printH
        halt
```

translating array sum (1)

```
read a;
read n;
i = 0;
s = 0;
while (i < n) {
   s += a[i];
   i += 1;
}
print s;
```

```
label  instr comment
        jmp start
i       dw 0
s       dw 0
n       dw 0
one     dw 1
zero    dw 0
addInst    dw 5000    add inst to fill in
start  readH                read array address
       store     a
       readH                read array size
       store     n
       load      zero
       store     i          i = 0
       store     s          s = 0
loop   load      n          if (i >= N) goto xit
       ...
xit    load s
       printH
       halt
```

translating array sum (2)

```
read a;
read n;
i = 0;
s = 0;
while (i < n) {
   s += a[i];
   i += 1;
}
print s;
```

```
label instr      comment
...
addInst  dw 5000    add inst to fill in
...
loop   load      n       if (i >= N) goto xit
       sub       i
       jmpl      xit
       jmpe      xit
       load      addInst
       add       a
       add       i
       store     doit    plant inst into the code
       load      s       s = s + ...
doit   dw        0 <-- replaced with 'add (a+i)'
       store s
       load i
       add  one
       store i
       jmp loop
```

translating array sum (2)

```
read a;
read n;
i = 0;
s = 0;
while (i < n) {
   s += a[i];
   i += 1;
}
print s;
```

```
label  instr        comment
...
addInst  dw 5000    add inst to fill in
...
loop   load     n       if (i >= N) goto xit
       sub      i
       jmpl     xit
       jmpe     xit
       load     addInst
       add      a
       add      i
       store    doit    plant inst into the code
       load     s       s = s + ...
doit   dw       0 <-- replaced with 'add (a+i)'
       store s
       load i
       add  one
       store i
       jmp  loop
```

translating array sum (2)

```
read a;
read n;
i = 0;
s = 0;
while (i < n) {
   s += a[i];
   i += 1;
}
print s;
```

```
label instr      comment
...
addInst  dw 5000    add inst to fill in
...
loop   load      n         if (i >= N) goto xit
       sub       i
       jmpl      xit
       jmpe      xit
       load      addInst
       add       a
       add       i
       store     doit    plant inst into the code
       load      s       s = s + ...
doit   dw        0 <-- replaced with 'add (a+i)'
       store s

       load i
       add  one
       store i
       jmp loop
```

translating array sum (2)

```
read a;
read n;
i = 0;
s = 0;
while (i < n) {
   s += a[i];
   i += 1;
}
print s;
```

```
label  instr         comment
...
addInst  dw 5000     add inst to fill in
...
loop   load      n       if (i >= N) goto xit
       sub       i
       jmpl      xit
       jmpe      xit
       load      addInst
       add       a
       add       i
       store     doit    plant inst into the code
       load      s       s = s + ...
doit   dw        0 <-- replaced with 'add (a+i)'
       store s
       load i
       add  one
       store i
       jmp  loop
```

translating array sum (2)

```
read a;
read n;
i = 0;
s = 0;
while (i < n) {
   s += a[i];
   i += 1;
}
print s;
```

```
label instr      comment
...
addInst  dw 5000    add inst to fill in
...
loop    load       n       if (i >= N) goto xit
        sub        i
        jmpl       xit
        jmpe       xit
        load      addInst
        add       a
        add       i
        store     doit    plant inst into the code
        load      s       s = s + ...
doit    dw        0 <-- replaced with 'add (a+i)'
        store s
        load i
        add  one
        store i
        jmp loop
```

translating array sum (2)

```
read a;
read n;
i = 0;
s = 0;
while (i < n) {
   s += a[i];
   i += 1;
}
print s;
```

```
label   instr        comment
...
addInst  dw 5000     add inst to fill in
...
loop    load      n        if (i >= N) goto xit
        sub       i
        jmpl      xit
        jmpe      xit
        load      addInst
        add       a
        add       i
        store     doit     plant inst into the code
        load      s        s = s + ...
doit    dw        0 <-- replaced with 'add (a+i)'
        store s
        load i
        add  one
        store i
        jmp  loop
```

translating array sum (2)

```
read a;
read n;
i = 0;
s = 0;
while (i < n) {
   s += a[i];
   i += 1;
}
print s;
```

```
label instr       comment
...
addInst  dw 5000    add inst to fill in
...
loop   load       n        if (i >= N) goto xit
       sub        i
       jmpl       xit
       jmpe       xit
         load       addInst
         add        a
         add        i
         store      doit    plant inst into the code
         load       s       s = s + ...
doit     dw         0 <-- replaced with 'add (a+i)'
         store s
         load i
         add  one
         store i
         jmp  loop
```

writing IBCM

high level pseudocode

```
i = 1;
while (i < max) ...
```

IBCM assembly code

```
load  one
store i
...
```

test by hand (trace code)

IBCM machine code

```
3016
4005
...
```

run in IBCM simulator

code is just data

IBCM had array of ‘words’ (16-bit values)

could be data or code or both

how to know which?

- what is the machine trying to do when it read/writes it?
- (e.g. `jmp` or `load`)

how typical modern computers work

code+data together machine: ‘von Neumann architecture’

- seperate code+data memory: ‘Harvard architecture’

IBCM can do...

IBCM can do “anything”

formally: Turing complete (if extended to infinitely large memory)

formal definition: see CS 3102

writing IBCM

high level pseudocode

```
i = 1;
while (i < max) ...
```

IBCM assembly code

```
load  one
store i
...
```

test by hand (trace code)

IBCM machine code

```
3016
4005
...
```

run in IBCM simulator

IBCM tips

write assembly code first

- use comments (for you and us)

write machine code last

check functionality in simulator

NB: simulator does not accept blank/comment lines

simulators and infinite loops

online simulator won't like infinite loops

- likely reason for web page just not responding

debugging advice

check program logic

- correct conditions for jmpl/jmpe?

check machine code translation

- follow decoding steps
- verify addresses

mssing from IBCM

multiply, divide

floating point

bigger addresses or values

more registers (and ability to specify registers)

...

implementing IBCM

```
unsigned short memory[4096];
unsigned short pc, ir, accum;
bool done = false;
while (!done) {
    ir = memory[pc];
    switch (extractOpcode(ir)) {
    case 0:
        // halt
        done = true;
        break;
    case 1:
        // I/O
        ...
    }
```

implementing IBCM

```
unsigned short memory[4096];
unsigned short pc, ir, accum;
bool done = false;
while (!done) {
    ir = memory[pc];
    switch (extractOpcode(ir)) {
    case 0:
        // halt
        done = true;
        break;
    case 1:
        // I/O
        ...
    }
```

extracting parts of instructions

assuming instruction in `instr`:

```
unsigned int opcode = (instr >> 12) & 0x000f;
unsigned int ioOrShiftOp = (instr >> 10) & 0x0003;
unsigned int address = instr & 0x0fff;
unsigned int shiftCount = instr & 0x000f;
```

`>>` — shift right

`&` — bitwise (bit-by-bit) and

extracting parts of instructions

assuming instruction in `instr`:

```
unsigned int opcode = (instr >> 12) & 0x000f;
unsigned int ioOrShiftOp = (instr >> 10) & 0x0003;
unsigned int address = instr & 0x0fff;
unsigned int shiftCount = instr & 0x000f;
```

`>>` — shift right

`&` — bitwise (bit-by-bit) and

---

but, isn't this very cumbersome???

encoding instructions

assuming instruction in `instr`:

```
unsigned int instr = (opcode << 12) | address;
unsigned int instr = (opcode << 12) | (ioOrShiftOp <
```

`<<` — shift right

`|` — bitwise (bit-by-bit) or

encoding instructions

assuming instruction in `instr`:

```
unsigned int instr = (opcode << 12) | address;
unsigned int instr = (opcode << 12) | (ioOrShiftOp <
```

`<<` — shift right

`|` — bitwise (bit-by-bit) or

---

but, isn't this very cumbersome???

C++ support for bit-extraction (1)

```
// assumes unsigned short is 16 bits
// and most common compiler convention for ordering
union ibcm_instruction {
    unsigned short value;
    struct { unsinged op: 4, ioOp: 2,
                      unused: 10; } io;
    struct { unsinged op: 4, shiftOp: 2,
                      shiftCount: 5; } shifts;
    struct { unsigned op: 4,
                      address: 12; } others;
};
```

C++ support for bit-extraction (2)

```
union ibcm_instruction i;
i.value = memory[pc];
switch (i.others.op) {
    ...
}
```

on bit fields

`value : 4` — called 'a bit field'

technically, order of bits can vary between compilers