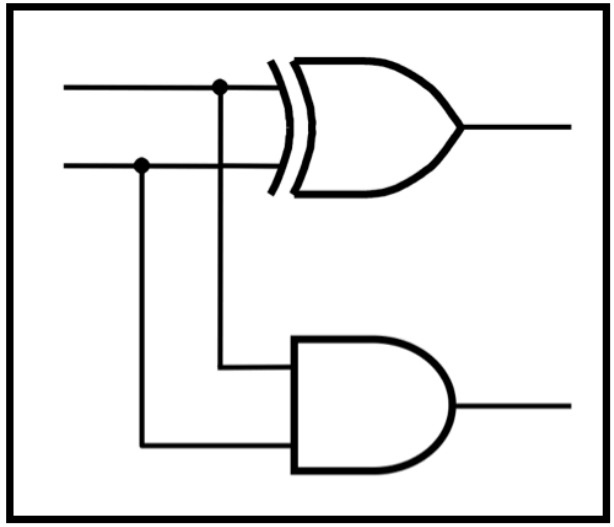


CprE 281: Digital Logic

Instructor: Alexander Stoytchev

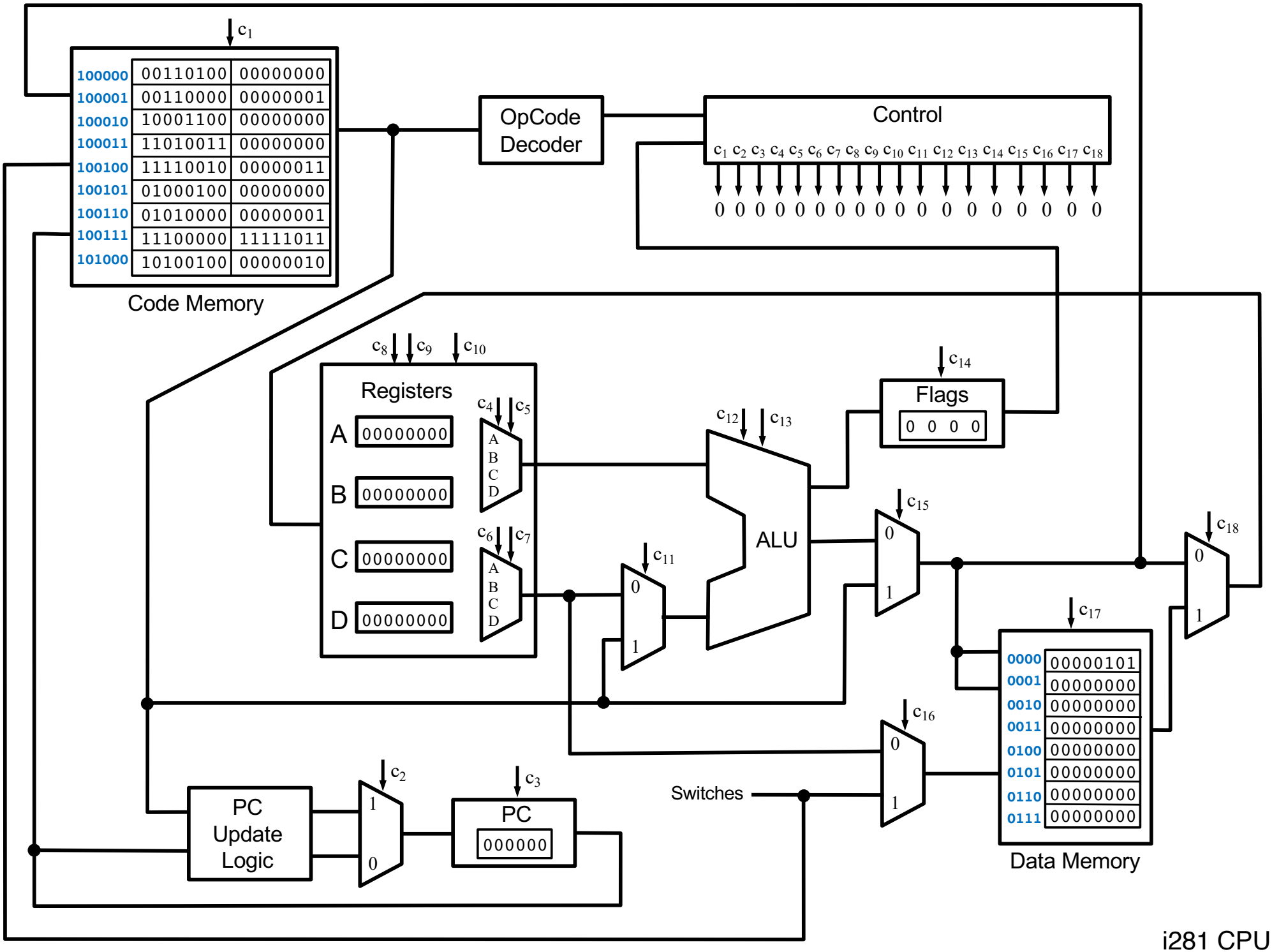
http://www.ece.iastate.edu/~alexs/classes/

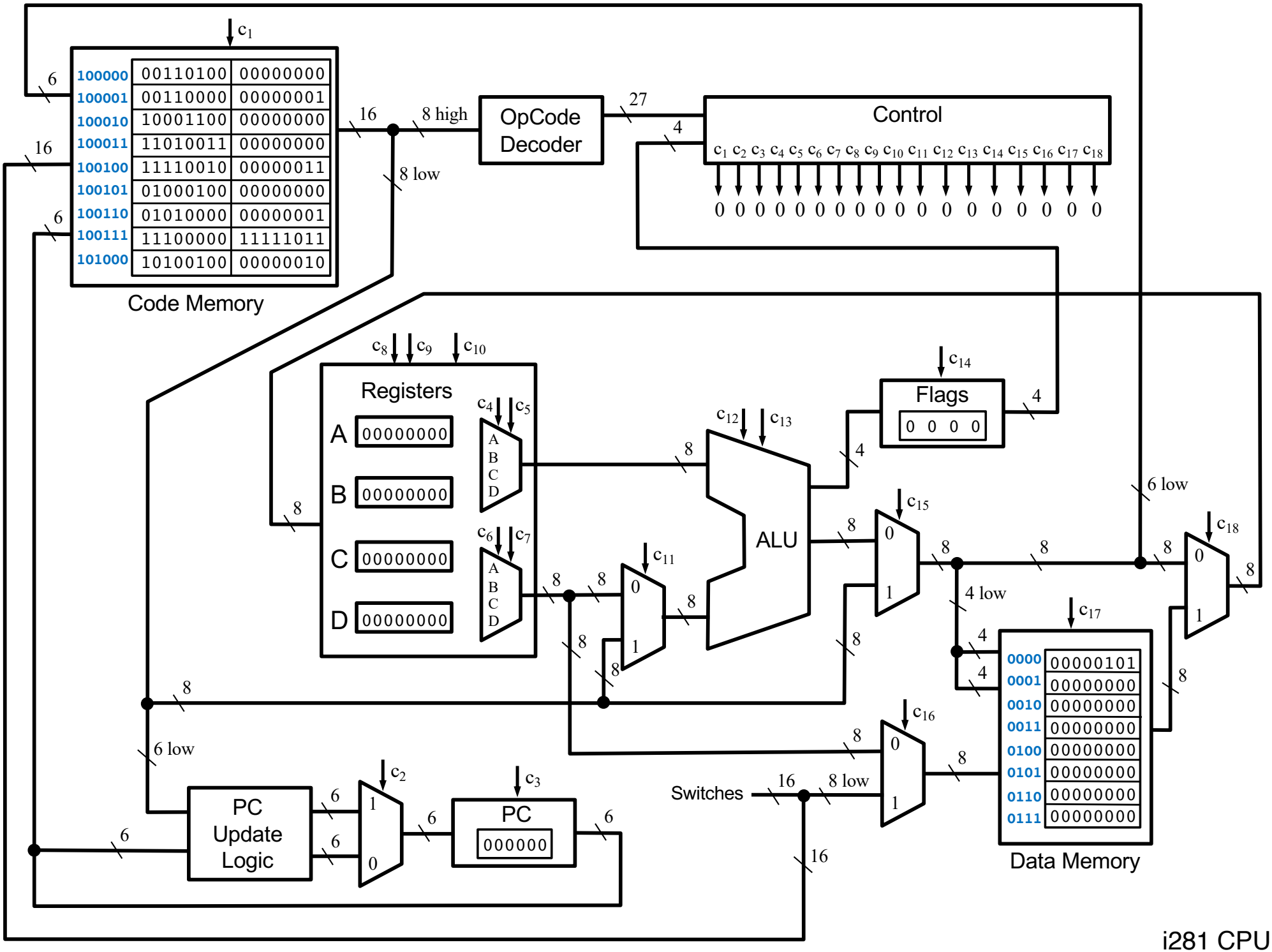
Assembly Examples

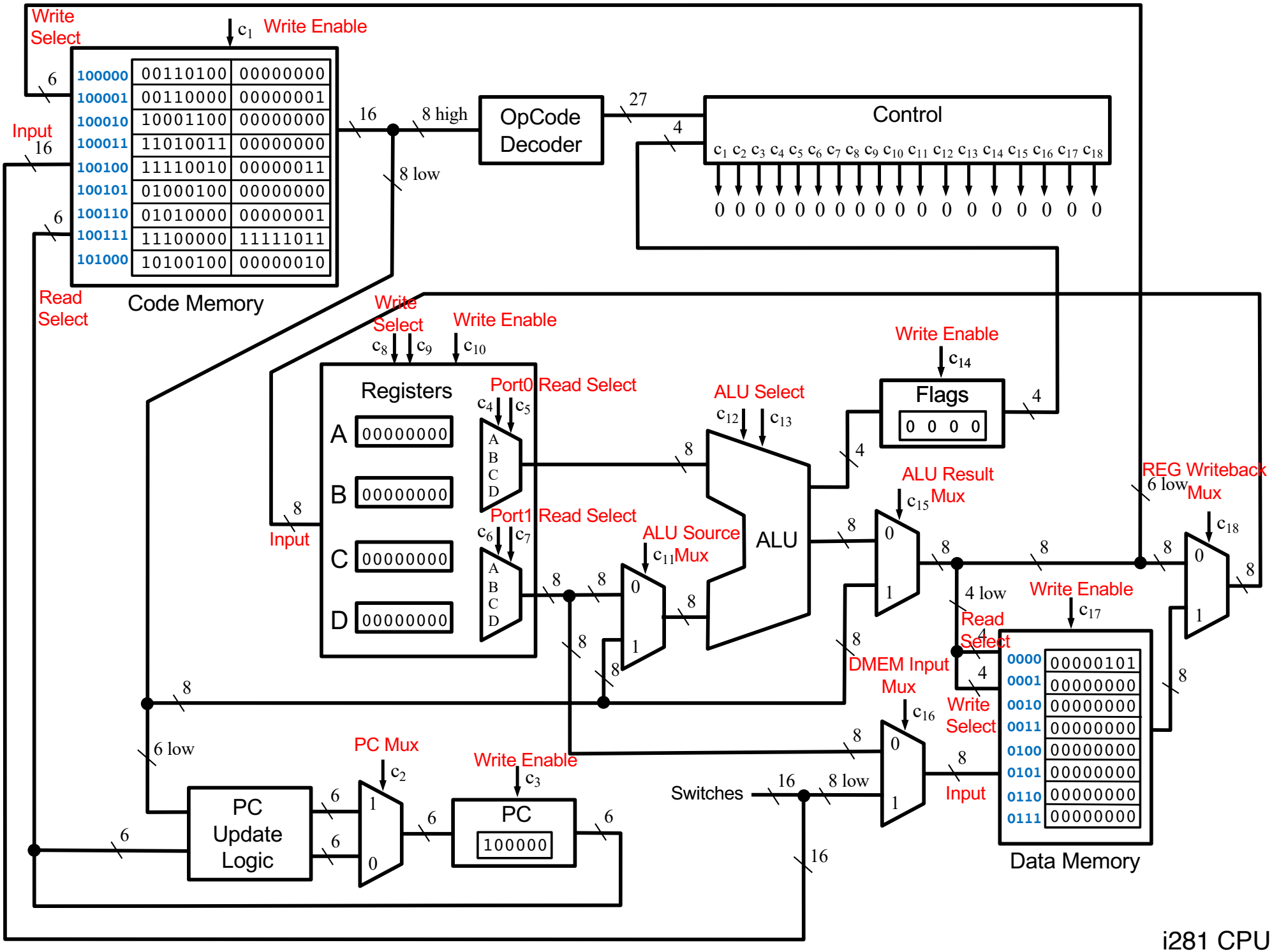
CprE 281: Digital Logic
Iowa State University, Ames, IA

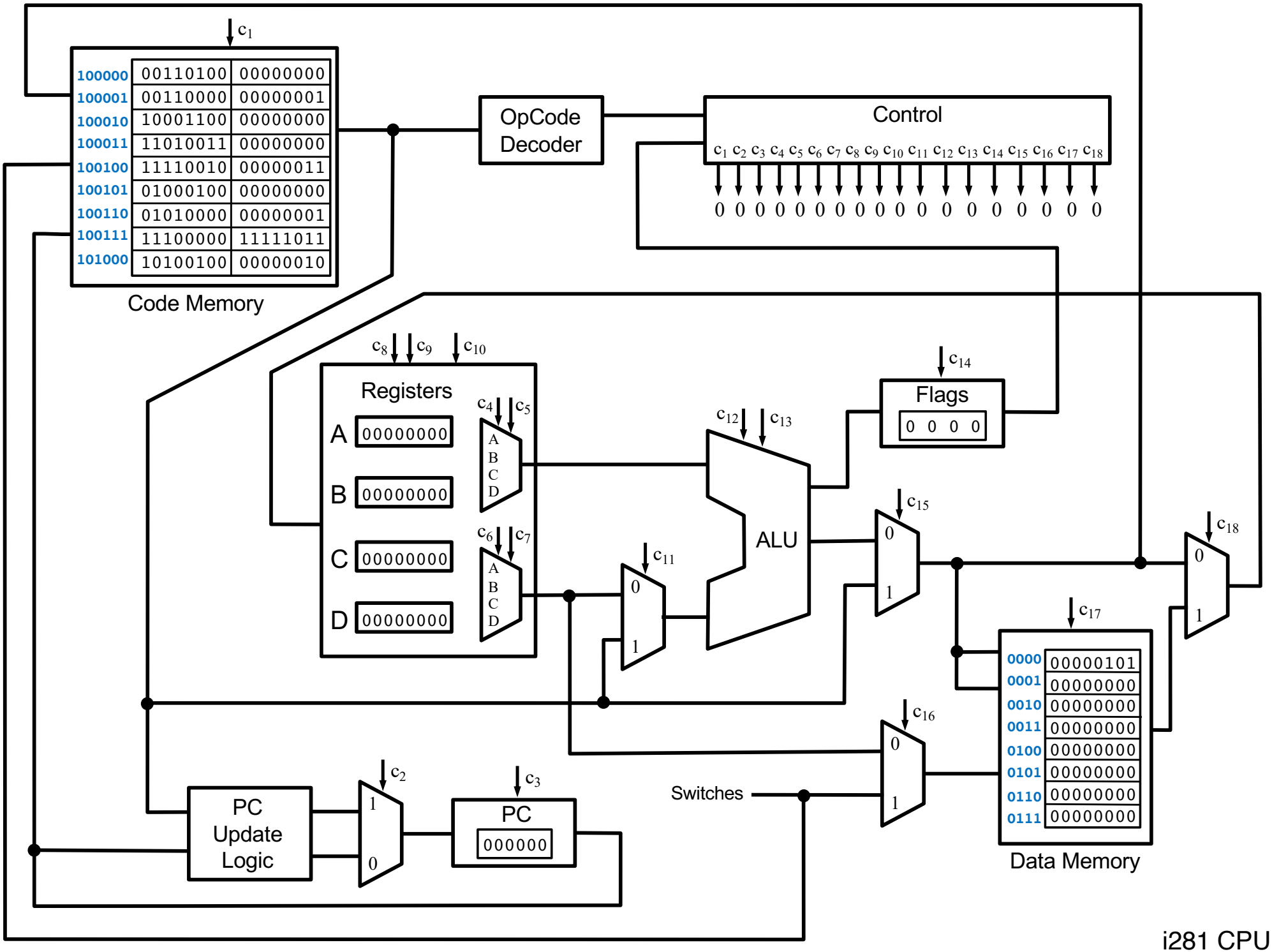
Assembly Examples
(for the i281 CPU)

CprE 281: Digital Logic
Iowa State University, Ames, IA


c1
100000 00110100 00000000
100001 00110000 00000001
100010 10001100 00000000
100011 11010011 00000000
100100 11110010 00000011
100101 01000100 00000000
100110 01010000 00000001
100111 11100000 11111011
101000 10100100 00000010
Code Memory
OpCode Decoder
Control
c1 c2 c3 c4 c5 c6 c7 c8 c9 c10 c11 c12 c13 c14 c15 c16 c17 c18
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
c8 c9 c10
Registers
A 00000000
B 00000000
C 00000000
D 00000000
c4 c5
c6 c7
A B C D
c14
Flags
0 0 0 0
c12 c13
ALU
c15
c11
0 1
c18
c17
0000 00000101
0001 00000000
0010 00000000
0011 00000000
0100 00000000
0101 00000000
0110 00000000
0111 00000000
Data Memory
c16
Switches
c2
c3
PC Update Logic
PC
000000
i281 CPU


c1
6
100000 00110100 00000000
100001 00110000 00000001
100010 10001100 00000000
100011 11010011 00000000
100100 11110010 00000011
100101 01000100 00000000
100110 01010000 00000001
100111 11100000 11111011
101000 10100100 00000010
Code Memory
16
8 high
8 low
OpCode Decoder
27
4
Control
c1 c2 c3 c4 c5 c6 c7 c8 c9 c10 c11 c12 c13 c14 c15 c16 c17 c18
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
c8 c9 c10
Registers
A 00000000
B 00000000
C 00000000
D 00000000
c4 c5
c6 c7
A B C D
8
c14
Flags
0 0 0 0
4
c12 c13
ALU
c11
c15
c16
c17
c18
6 low
4 low
Switches
16
8 low
0000 00000101
0001 00000000
0010 00000000
0011 00000000
0100 00000000
0101 00000000
0110 00000000
0111 00000000
Data Memory
6 low
PC Update Logic
c2
c3
PC
000000
i281 CPU


Write Select
c1 Write Enable
6
100000 00110100 00000000
100001 00110000 00000001
100010 10001100 00000000
100011 11010011 00000000
100100 11110010 00000011
100101 01000100 00000000
100110 01010000 00000001
100111 11100000 11111011
101000 10100100 00000010
Code Memory
Input
16
6
Read Select
16
8 high
8 low
OpCode Decoder
27
4
Control
c1 c2 c3 c4 c5 c6 c7 c8 c9 c10 c11 c12 c13 c14 c15 c16 c17 c18
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
Write Select
c8 c9
Write Enable
c10
Registers
A 00000000
B 00000000
C 00000000
D 00000000
Port0 Read Select
c4 c5
Port1 Read Select
c6 c7
A B C D
8
Input
ALU Select
c12 c13
ALU
Write Enable
c14
Flags
0 0 0 0
4
ALU Source
c11 Mux
ALU Result
c15 Mux
REG Writeback
6 low
Mux
c18
4 low
Read Select
Write Enable
c17
DMEM Input
Mux
c16
Write Select
0000 00000101
0001 00000000
0010 00000000
0011 00000000
0100 00000000
0101 00000000
0110 00000000
0111 00000000
Data Memory
Switches
16
8 low
Input
PC Mux
c2
Write Enable
c3
PC
100000
6 low
PC Update Logic
6
16
i281 CPU


c1
100000 00110100 00000000
100001 00110000 00000001
100010 10001100 00000000
100011 11010011 00000000
100100 11110010 00000011
100101 01000100 00000000
100110 01010000 00000001
100111 11100000 11111011
101000 10100100 00000010
Code Memory
OpCode Decoder
Control
c1 c2 c3 c4 c5 c6 c7 c8 c9 c10 c11 c12 c13 c14 c15 c16 c17 c18
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
c8 c9 c10
Registers
A 00000000
B 00000000
C 00000000
D 00000000
c4 c5
c6 c7
A B C D
c14
Flags
0 0 0 0
c12 c13
ALU
c15
c11
0 1
c18
c17
0000 00000101
0001 00000000
0010 00000000
0011 00000000
0100 00000000
0101 00000000
0110 00000000
0111 00000000
Data Memory
c16
Switches
c2
c3
PC Update Logic
PC
000000
i281 CPU

The Assembly Language Instructions

The i281 Assembly Instructions

NOOP	NO OPeration
INPUTC	INPUT into Code memory
INPUTCF	INPUT into Code memory with oFfset
INPUTD	INPUT into Data memory
INPUTDF	INPUT into Data memory with oFfset
MOVE	MOVE the contents of one register into another
LOADI	LOAD Immediate value
LOADP	LOAD Pointer address
ADD	ADD two registers
ADDI	ADD an Immediate value to a register
SUB	SUBtract two registers
SUBI	SUBtract an Immediate value from a register
LOAD	LOAD from a data memory address into a register
LOADF	LOAD with an oFfset specified by another register
STORE	STORE a register into a data memory address
STOREF	STORE with an oFfset specified by another register
SHIFTL	SHIFT Left all bits in a register
SHIFTR	SHIFT Right all bits in a register
CMP	CoMPare the values in two registers
JUMP	JUMP unconditionally to a specified address
BRE	BRanch if Equal
BRZ	BRanch if Zero
BRNE	BRanch if Not Equal
BRNZ	BRanch if Not Zero
BRG	BRanch if Greater
BRGE	BRanch if Greater than or Equal

The i281 Assembly Instructions

NOOP	NO OPeration
INPUTC	INPUT into Code memory
INPUTCF	INPUT into Code memory with oFfset
INPUTD	INPUT into Data memory
INPUTDF	INPUT into Data memory with oFfset
MOVE	MOVE the contents of one register into another
LOADI	LOAD Immediate value
LOADP	LOAD Pointer address
ADD	ADD two registers
ADDI	ADD an Immediate value to a register
SUB	SUBtract two registers
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SHIFTL	SHIFT Left all bits in a register
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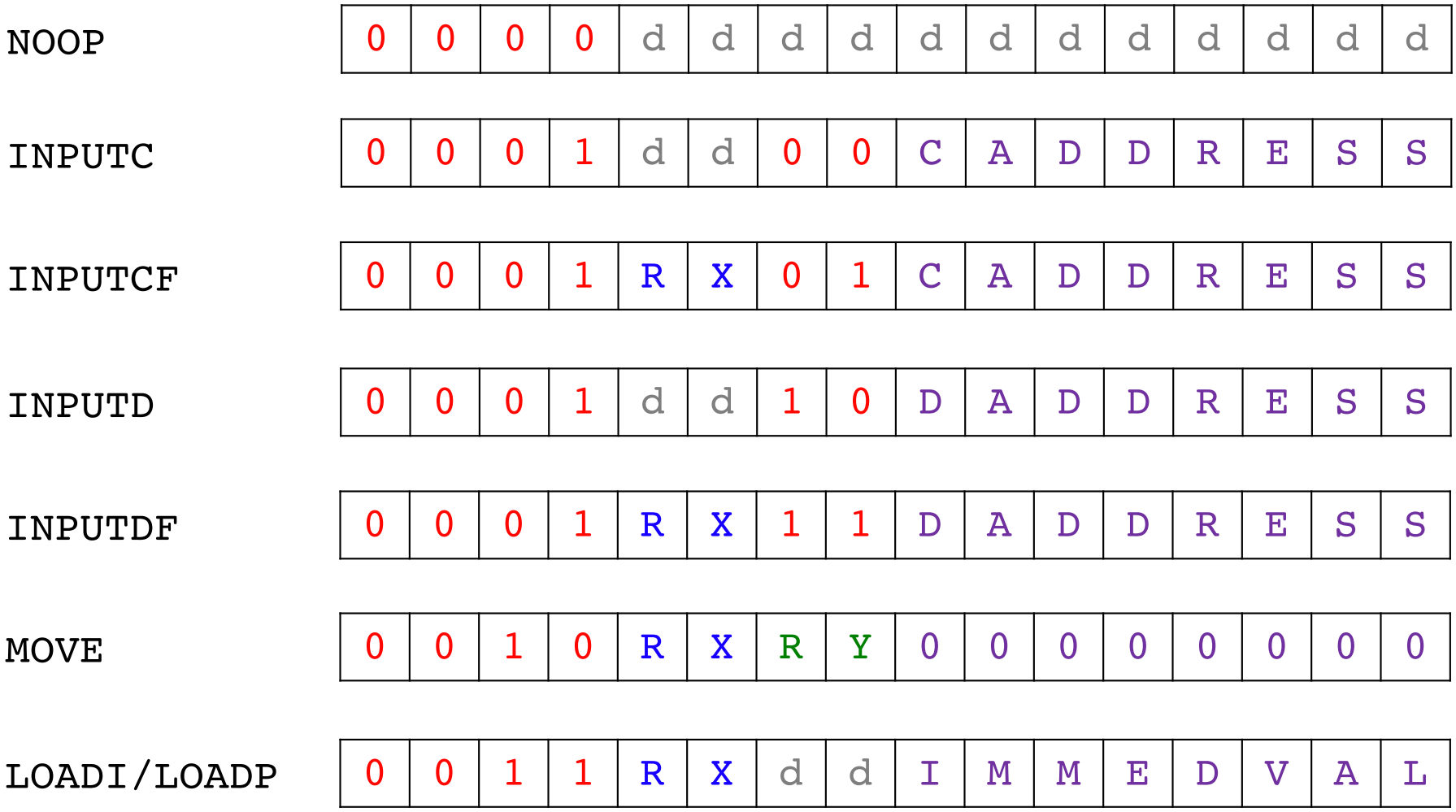
JUMP	JUMP unconditionally to a specified address
BRE	BRanch if Equal
BRZ	BRanch if Zero
BRNE	BRanch if Not Equal
BRNZ	BRanch if Not Zero
BRG	BRanch if Greater
BRGE	BRanch if Greater than or Equal

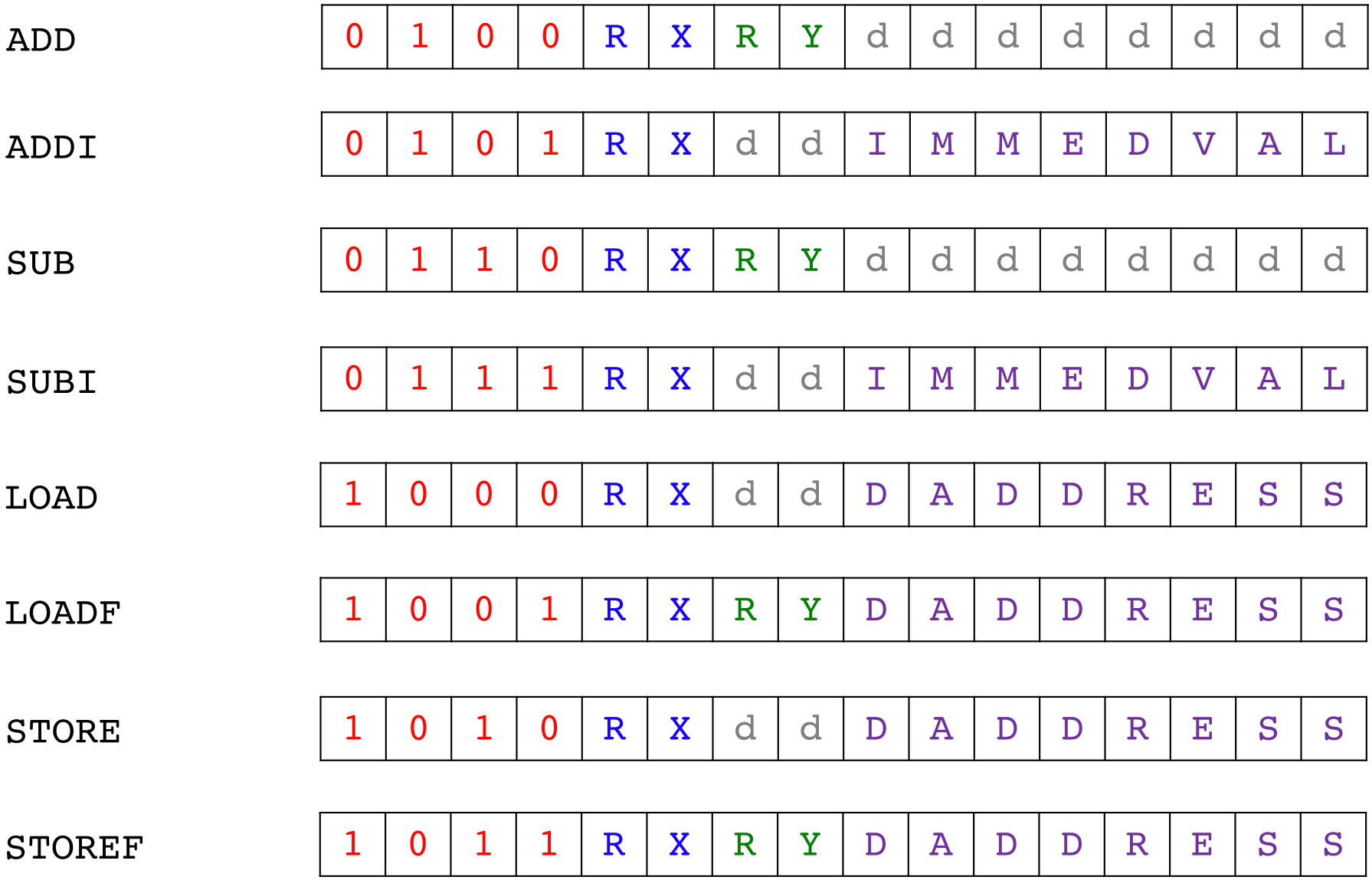
The OPCODEs

(Mapped to Machine Language)

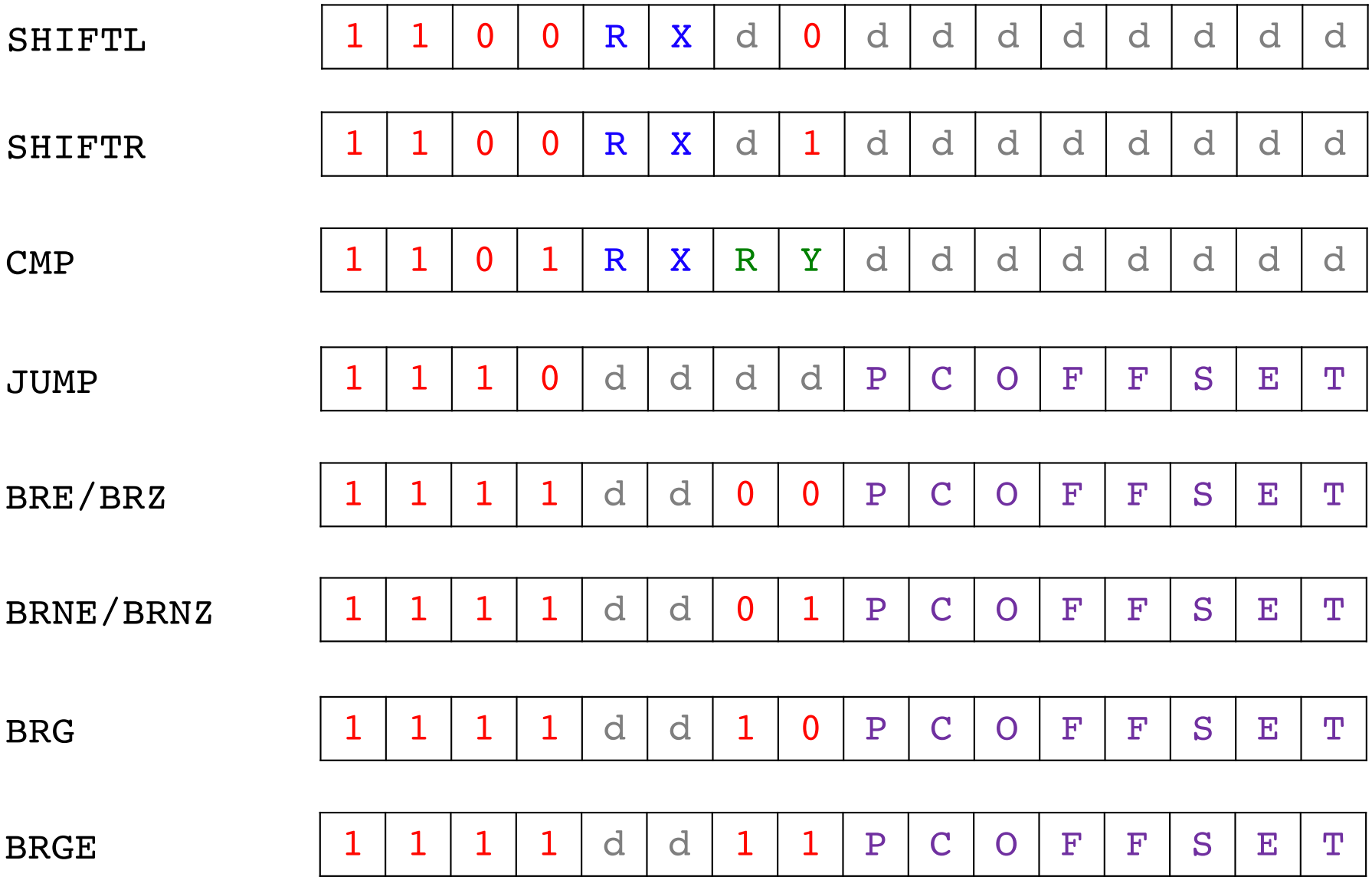
The OPCODEs


NOOP
0 0 0 0 d d d d d d d d d d d d
INPUTC
0 0 0 1 d d 0 0 C A D D R E S S
INPUTCF
0 0 0 1 R X 0 1 C A D D R E S S
INPUTD
0 0 0 1 d d 1 0 D A D D R E S S
INPUTDF
0 0 0 1 R X 1 1 D A D D R E S S
MOVE
0 0 1 0 R X R Y 0 0 0 0 0 0 0 0
LOADI/LOADP
0 0 1 1 R X d d I M M E D V A L

The OPCODEs


ADD
0 1 0 0 R X R Y d d d d d d d d
ADDI
0 1 0 1 R X d d I M M E D V A L
SUB
0 1 1 0 R X R Y d d d d d d d d
SUBI
0 1 1 1 R X d d I M M E D V A L
LOAD
1 0 0 0 R X d d D A D D R E S S
LOADF
1 0 0 1 R X R Y D A D D R E S S
STORE
1 0 1 0 R X d d D A D D R E S S
STOREF
1 0 1 1 R X R Y D A D D R E S S

The OPCODEs


SHIFTL
1 1 0 0 R X d 0 d d d d d d d d
SHIFTR
1 1 0 0 R X d 1 d d d d d d d d
CMP
1 1 0 1 R X R Y d d d d d d d d
JUMP
1 1 1 0 d d d d P C O F F S E T
BRE/BRZ
1 1 1 1 d d 0 0 P C O F F S E T
BRNE/BRNZ
1 1 1 1 d d 0 1 P C O F F S E T
BRG
1 1 1 1 d d 1 0 P C O F F S E T
BRGE
1 1 1 1 d d 1 1 P C O F F S E T

Sample Assembly Programs for the i281 CPU

Arithmetic

C Version

```
// Arithmetic1
//
// C version


int main()
{
        int x=2;
        int z;

        z = x+3;

        // printf("%d\n", z);
}
```

Assembly Version

```
; Assembly version

.data
x         BYTE         2
z         BYTE         ?


.code
        LOAD  A, [x]
        MOVE  C, A          ; z=x;
        ADDI  C, 3          ; z+=3;
        STORE [z], C        ; update the memory for z


; Register allocation
;
; A: x
; B: <not used>
; C: z
; D: <not used>
```

C vs. Assembly

```c
// Arithmetic1
//
// C version


int main()
{
        int x=2;
        int z;

        z = x+3;

        // printf("%d\n", z);
}
```

```
; Assembly version

.data
x         BYTE         2
z         BYTE         ?


.code
        LOAD   A, [x]
        MOVE   C, A          ; z=x;
        ADDI   C, 3          ; z+=3;
        STORE  [z], C        ; update the
                             ; memory for z
```

Arithmetic 2

C Version

```
// Arithmetic 2
//
// C version


int main()
{
        int x=2;
        int y=3;
        int z;

        z = x+y;

        // printf("%d\n", z);
}
```

Assembly Version

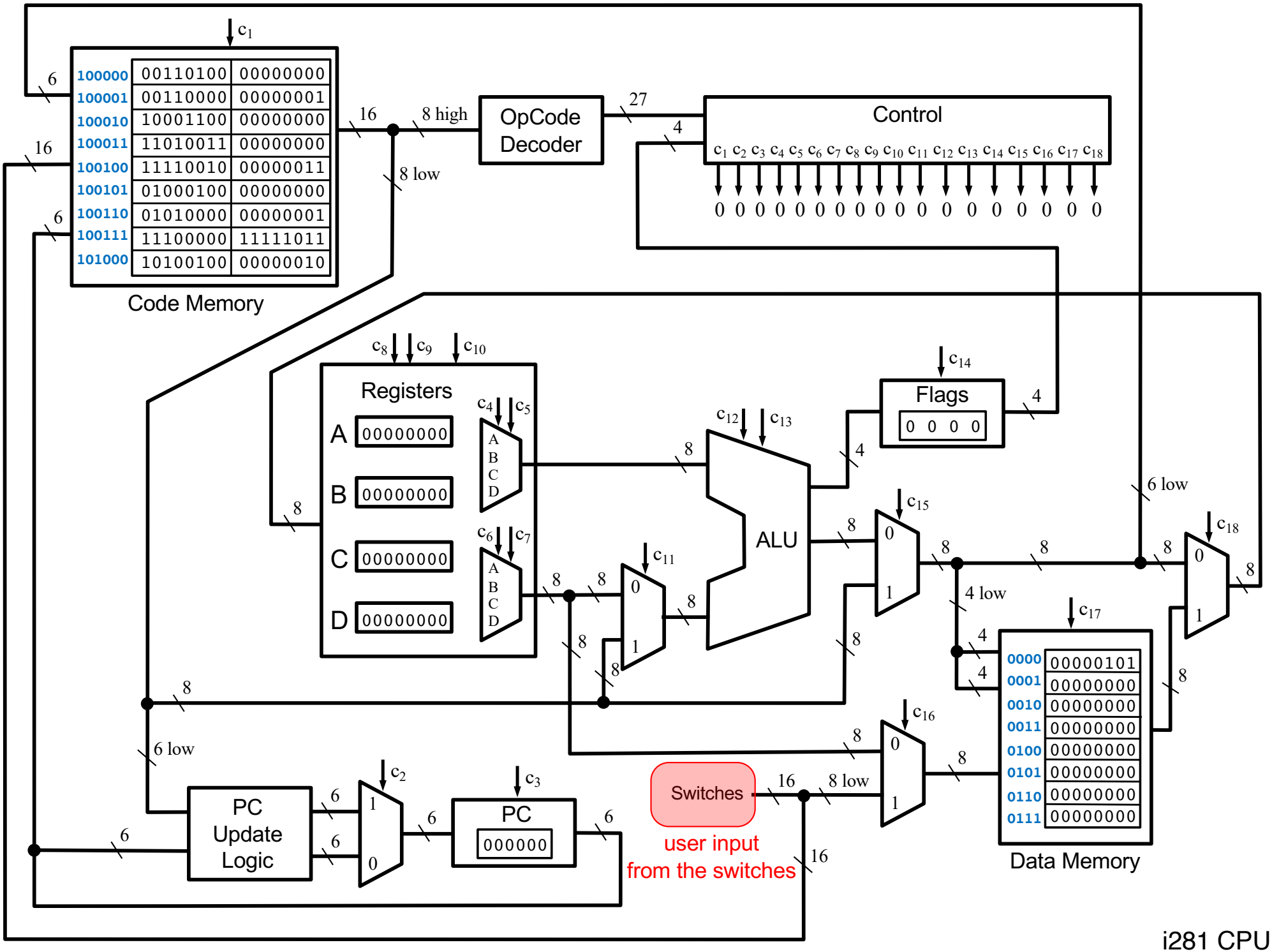
```
; Arithmetic 2
; Assembly version

.data
x         BYTE        2
y         BYTE        3
z         BYTE        ?

.code
        LOAD  A, [x]
        LOAD  B, [y]
        MOVE  C, A          ; z=x;
        ADD   C, B          ; z+=y;
        STORE [z], C

; Register allocation
;
; A: x
; B: y
; C: z
; D: <not used>
```

C vs. Assembly

```c
// Arithmetic 2
//
// C version


int main()
{
        int x=2;
        int y=3;
        int z;

        z = x+y;

        // printf("%d\n", z);
}
```

```
; Arithmetic 2
; Assembly version

.data
x       BYTE        2
y       BYTE        3
z       BYTE        ?

.code
        LOAD  A, [x]
        LOAD  B, [y]
        MOVE  C, A          ; z=x;
        ADD   C, B          ; z+=y;
        STORE [z], C
```

User Input from the Switches (arithmetic example)


c1
100000 00110100 00000000
100001 00110000 00000001
100010 10001100 00000000
100011 11010011 00000000
100100 11110010 00000011
100101 01000100 00000000
100110 01010000 00000001
100111 11100000 11111011
101000 10100100 00000010
Code Memory
6
16
16
8 high
8 low
OpCode Decoder
27
4
Control
c1 c2 c3 c4 c5 c6 c7 c8 c9 c10 c11 c12 c13 c14 c15 c16 c17 c18
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
c8 c9 c10
Registers
A 00000000
B 00000000
C 00000000
D 00000000
c4 c5
c6 c7
A B C D
8
c14
Flags
0 0 0 0
4
c12 c13
ALU
c11
c15
c16
c17
c18
6 low
4 low
8 low
0000 00000101
0001 00000000
0010 00000000
0011 00000000
0100 00000000
0101 00000000
0110 00000000
0111 00000000
Data Memory
PC Update Logic
c2
c3
PC
000000
Switches
user input from the switches

i281 CPU

C vs. Assembly

```c
#include<stdio.h>

int x = 2;
int y;
int result;

// Addition with User input
// for the second variable (y)

void main()
{

     scanf("%d", &y);

     result = x + y;

     //printf("%d", result);

}
```

```
; Arithmetic with user input from switches
; Assembly version

.data
x          BYTE 2
y          BYTE ?
result     BYTE ?

.code

        LOAD    A, [x]          ; Reg. A <- [x]
        INPUTD  [y]             ; [y] <- Input
        LOAD    B, [y]          ; Reg. B <- [y]
        ADD     A, B            ; A <- A + B
        STORE   [result], A     ; result <- Reg A
```

C vs. Assembly

```c
#include<stdio.h>

int x = 2;
int y;
int result;

// Addition with User input
// for the second variable (y)

void main()
{

     scanf("%d", &y);

     result = x + y;

     //printf("%d", result);

}
```

```
; Arithmetic with user input from switches
; Assembly version

.data
x          BYTE 2
y          BYTE ?
result     BYTE ?

.code

        LOAD    A, [x]          ; Reg. A <- [x]
        INPUTD  [y]             ; [y] <- Input
        LOAD    B, [y]          ; Reg. B <- [y]
        ADD     A, B            ; A <- A + B
        STORE   [result], A     ; result <- Reg A
```

Read the current value from switches SW07 to SW01 and store this value in the DMEM cell with label y.

Multiplication

C Version

```
// Multiplication
//
// C version


int main()
{
        int x=2;
        int z;

        z = x*5;

        // printf("%d\n", z);
}
```

Assembly Version

```
; Multiplication

.data
x         BYTE        3
z         BYTE        ?

.code
        LOAD    A, [x]
        MOVE    C, A          ; z=x;
        MOVE    B, A          ; B=x;
        SHIFTL  B             ; B=2x
        SHIFTL  B             ; B=4x
        ADD     C, B          ; C=4x+x
        STORE   [z], C        ; update the memory for z

; Register allocation
;
; A: x
; B: temporary results for 2x and 4x
; C: z
; D: <not used>
```

C vs. Assembly

```c
// Multiplication
//
// C version


int main()
{
        int x=2;
        int z;

        z = x*5;

        // printf("%d\n", z);
}
```

```
; Multiplication

.data
x         BYTE         3
z         BYTE         ?

.code
        LOAD    A, [x]
        MOVE    C, A          ; z=x;
        MOVE    B, A          ; B=x;
        SHIFTL  B             ; B=2x
        SHIFTL  B             ; B=4x
        ADD     C, B          ; C=4x+x
        STORE   [z], C        ; update the
                              ; memory for z
```

Multiplication
(implemented with repeated addition)

C Version

```
// Multiplication
//
// C version


int main()
{
        int x=2;
        int z;

        z = x*5;

        // printf("%d\n", z);
}
```

C Version

```
// Multiplication
//
// C version


int main()
{
        int x=3;
        int z=0;

        for(int i=0; i<5; i++){
            z+=x;
        }
        // printf("%d\n", z);
}
```

Assembly Version

```
; Assembly version
;
; The CPU does not have OPCODEs for multiplication.
; Therefore, it is emulated with repeated addition.

.data
x         BYTE        3
z         BYTE        ?

.code
          LOAD  A, [x]
          LOADI C, 0          ; z=0
          LOADI B, 0          ; i=0
          LOADI D, 5          ; sentinel value
For:      CMP   B, D          ; i<5?
          BRGE  End           ; if(i>=5), exit for loop
          ADD   C, A          ; z+=x
          ADDI  B, 1          ; i++
          JUMP  For           ; jump to For loop
End:      STORE [z], C        ; update the z value in memory
```

Assembly Version

```
; Assembly version
;
; The CPU does not have OPCODEs for multiplication.
; Therefore, it is emulated with repeated addition.

.data
x         BYTE        3
z         BYTE        ?

.code
          LOAD  A, [x]
          LOADI C, 0          ; z=0
          LOADI B, 0          ; i=0
          LOADI D, 5          ; sentinel value
For:      CMP   B, D          ; i<5?
          BRGE  End           ; if(i>=5), exit for loop
          ADD   C, A          ; z+=x
          ADDI  B, 1          ; i++
          JUMP  For           ; jump to For loop
End:      STORE [z], C        ; update the z value in memory
```

```
; Register allocation
;
; A: x
; B: i (optimized to register)
; C: z
; D: 5
```

C vs. Assembly

```c
// Multiplication
//
// C version


int main()
{

    int x=3;
    int z=0;

    for(int i=0; i<5; i++){
         z+=x;
    }
    // printf("%d\n", z);
}
```

```
; Assembly version

.data
x         BYTE        3
z         BYTE        ?

.code
          LOAD  A, [x]
          LOADI C, 0          ; z=0
          LOADI B, 0          ; i=0
          LOADI D, 5          ; sentinel value
For:      CMP   B, D          ; i<5?
          BRGE  End           ; if(i>=5), exit loop
          ADD   C, A          ; z+=x
          ADDI  B, 1          ; i++
          JUMP  For           ; jump to For loop
End:      STORE [z], C        ; update the z
                              ; value in memory
```

If Statement:
Comparison of Signed Numbers

The i281 Assembly Instructions

NOOP	NO OPeration
INPUTC	INPUT into Code memory
INPUTCF	INPUT into Code memory with oFfset
INPUTD	INPUT into Data memory
INPUTDF	INPUT into Data memory with oFfset
MOVE	MOVE the contents of one register into another
LOADI	LOAD Immediate value
LOADP	LOAD Pointer address
ADD	ADD two registers
ADDI	ADD an Immediate value to a register
SUB	SUBtract two registers
SUBI	SUBtract an Immediate value from a register
LOAD	LOAD from a data memory address into a register
LOADF	LOAD with an oFfset specified by another register
STORE	STORE a register into a data memory address
STOREF	STORE with an oFfset specified by another register
SHIFTL	SHIFT Left all bits in a register
SHIFTR	SHIFT Right all bits in a register
CMP	CoMPare the values in two registers
JUMP	JUMP unconditionally to a specified address
BRE	BRanch if Equal
BRZ	BRanch if Zero
BRNE	BRanch if Not Equal
BRNZ	BRanch if Not Zero
BRG	BRanch if Greater
BRGE	BRanch if Greater than or Equal

The i281 Assembly Instructions

NOOP	NO OPeration
INPUTC	INPUT into Code memory
INPUTCF	INPUT into Code memory with oFfset
INPUTD	INPUT into Data memory
INPUTDF	INPUT into Data memory with oFfset
MOVE	MOVE the contents of one register into another
LOADI	LOAD Immediate value
LOADP	LOAD Pointer address
ADD	ADD two registers
ADDI	ADD an Immediate value to a register
SUB	SUBtract two registers
SUBI	SUBtract an Immediate value from a register
LOAD	LOAD from a data memory address into a register
LOADF	LOAD with an oFfset specified by another register
STORE	STORE a register into a data memory address
STOREF	STORE with an oFfset specified by another register
SHIFTL	SHIFT Left all bits in a register
SHIFTR	SHIFT Right all bits in a register
CMP	CoMPare the values in two registers
JUMP	JUMP unconditionally to a specified address
BRE	BRanch if Equal
BRZ	BRanch if Zero
BRNE	BRanch if Not Equal
BRNZ	BRanch if Not Zero
BRG	BRanch if Greater
BRGE	BRanch if Greater than or Equal

These 6 are used to implement comparisons

The i281 Assembly Instructions

NOOP	NO OPeration
INPUTC	INPUT into Code memory
INPUTCF	INPUT into Code memory with oFfset
INPUTD	INPUT into Data memory
INPUTDF	INPUT into Data memory with oFfset
MOVE	MOVE the contents of one register into another
LOADI	LOAD Immediate value
LOADP	LOAD Pointer address
ADD	ADD two registers
ADDI	ADD an Immediate value to a register
SUB	SUBtract two registers
SUBI	SUBtract an Immediate value from a register
LOAD	LOAD from a data memory address into a register
LOADF	LOAD with an oFfset specified by another register
STORE	STORE a register into a data memory address
STOREF	STORE with an oFfset specified by another register
SHIFTL	SHIFT Left all bits in a register
SHIFTR	SHIFT Right all bits in a register
CMP	CoMPare the values in two registers
JUMP	JUMP unconditionally to a specified address
BRE	BRanch if Equal
BRZ	BRanch if Zero
BRNE	BRanch if Not Equal
BRNZ	BRanch if Not Zero
BRG	BRanch if Greater
BRGE	BRanch if Greater than or Equal
BRL	BRanch if Less
BRLE	BRanch if Less than or Equal

These two instructions are NOT supported by this CPU

The i281 Assembly Instructions

NOOP	NO OPeration
INPUTC	INPUT into Code memory
INPUTCF	INPUT into Code memory with oFfset
INPUTD	INPUT into Data memory
INPUTDF	INPUT into Data memory with oFfset
MOVE	MOVE the contents of one register into another
LOADI	LOAD Immediate value
LOADP	LOAD Pointer address
ADD	ADD two registers
ADDI	ADD an Immediate value to a register
SUB	SUBtract two registers
SUBI	SUBtract an Immediate value from a register
LOAD	LOAD from a data memory address into a register
LOADF	LOAD with an oFfset specified by another register
STORE	STORE a register into a data memory address
STOREF	STORE with an oFfset specified by another register
SHIFTL	SHIFT Left all bits in a register
SHIFTR	SHIFT Right all bits in a register
CMP	CoMPare the values in two registers
JUMP	JUMP unconditionally to a specified address
BRE	BRanch if Equal
BRZ	BRanch if Zero
BRNE	BRanch if Not Equal
BRNZ	BRanch if Not Zero
BRG	BRanch if Greater
BRGE	BRanch if Greater than or Equal
BRL	BRanch if Less
BRLE	BRanch if Less than or Equal

comparison of signed numbers only

Common Comparisons

```
(x < y)      (x <= y)      (x == y)      (x!= y)      (x >= y)      (x > y)
```

Common Comparisons

(x < y)	(x <= y)	(x == y)	(x!= y)	(x >= y)	(x > y)
CMP x,y	CMP x,y	CMP x,y	CMP x,y	CMP x,y	CMP x,y
BRGE End	BRG End	BRNE End	BRE End	BRL End	BRLE End

Where x and y are two registers.

Common Comparisons

(x < y)	(x <= y)	(x == y)	(x!= y)	(x >= y)	(x > y)
CMP x,y BRGE End	CMP x,y BRG End	CMP x,y BRNE End	CMP x,y BRE End	CMP x,y BRL End	CMP x,y BRLE End

These two instructions are NOT supported by this CPU.

Common Comparisons

Therefore, invert the order.

(x < y)	(x <= y)	(x == y)	(x!= y)	~~(x >= y)~~ (y <= x)	~~(x > y)~~ (y < x)
CMP x,y	CMP x,y	CMP x,y	CMP x,y	CMP x,y	CMP x,y
BRGE End	BRG End	BRNE End	BRE End	BRL End	BRLE End

Common Comparisons

(x < y)	(x <= y)	(x == y)	(x!= y)
CMP x,y	CMP x,y	CMP x,y	CMP x,y
BRGE End	BRG End	BRNE End	BRE End

Therefore, invert the order.

(y <= x)	(y < x)
~~(x >= y)~~	~~(x > y)~~
~~CMP x,y~~	~~CMP x,y~~
~~BRL End~~	~~BRLE End~~
CMP y,x	CMP y,x
BRG End	BRGE End

If Less

C vs. Assembly

```
// If Less
//
// C version



int main()
{

      int x=3;
      int y=5;
      int z=0;

      if(x < y)
         z=x;
}
```

```
; If Less
;
; Assembly version

.data
x       BYTE     3
y       BYTE     5
z       BYTE     0

.code
        LOAD  A, [x]
        LOAD  B, [y]
        CMP   A, B
        BRGE  End
        STORE [z], A
End:    NOOP
```

C vs. Assembly

```
// If Less
//
// C version



int main()
{

      int x=3;
      int y=5;
      int z=0;

      if(x < y)
         z=x;
}
```

```
; If Less
;
; Assembly version

.data
x       BYTE     3
y       BYTE     5
z       BYTE     0

.code
        LOAD   A, [x]
        LOAD   B, [y]
        CMP    A, B
        BRGE   End
        STORE [z], A
End:    NOOP
```

instead of x < y,
check if x >= y

If Less or Equal

C vs. Assembly

```
// If Less or Equal
//
// C version



int main()
{

      int x=3;
      int y=5;
      int z=0;

      if(x <= y)
         z=x;
}
```

```
; If Less or Equal
;
; Assembly version

.data
x       BYTE    3
y       BYTE    5
z       BYTE    0

.code
        LOAD  A, [x]
        LOAD  B, [y]
        CMP   A, B
        BRG   End
        STORE [z], A
End:    NOOP
```

C vs. Assembly

```
// If Less or Equal
//
// C version



int main()
{

      int x=3;
      int y=5;
      int z=0;

      if(x <= y)
         z=x;
}
```

```
; If Less or Equal
;
; Assembly version

.data
x       BYTE    3
y       BYTE    5
z       BYTE    0

.code
        LOAD    A, [x]
        LOAD    B, [y]
        CMP     A, B
        BRG     End
        STORE   [z], A
End:    NOOP
```

instead of x <= y,
check if x > y

If Equal

C vs. Assembly

```c
// If Equal
//
// C version



int main()
{

      int x=3;
      int y=5;
      int z=0;

      if(x==y)
         z=x;
}
```

```
; If Equal
;
; Assembly version

.data
x       BYTE   3
y       BYTE   5
z       BYTE   0

.code
        LOAD   A, [x]
        LOAD   B, [y]
        CMP    A, B
        BRNE   End
        STORE  [z], A
End:    NOOP
```

C vs. Assembly

```c
// If Equal
//
// C version



int main()
{

      int x=3;
      int y=5;
      int z=0;

      if(x==y)
         z=x;
}
```

```
; If Equal
;
; Assembly version

.data
x       BYTE    3
y       BYTE    5
z       BYTE    0

.code
        LOAD    A, [x]
        LOAD    B, [y]
        CMP     A, B
        BRNE    End
        STORE   [z], A
End:    NOOP
```

instead of x == y,
check if x != y

If Not Equal

C vs. Assembly

```
// If Not Equal
//
// C version



int main()
{

      int x=3;
      int y=5;
      int z=0;

      if(x != y)
         z=x;
}
```

```
; If Not Equal
;
; Assembly version

.data
x       BYTE    3
y       BYTE    5
z       BYTE    0

.code
        LOAD  A, [x]
        LOAD  B, [y]
        CMP   A, B
        BRE   End
        STORE [z], A
End:    NOOP
```

C vs. Assembly

```
// If Not Equal
//
// C version



int main()
{

      int x=3;
      int y=5;
      int z=0;

      if(x != y)
         z=x;
}
```

```
; If Not Equal
;
; Assembly version

.data
x       BYTE    3
y       BYTE    5
z       BYTE    0

.code
        LOAD    A, [x]
        LOAD    B, [y]
        CMP     A, B
        BRE     End
        STORE   [z], A
End:    NOOP
```

instead of x != y,
check if x == y

If Greater or Equal

C vs. Assembly

```
// If Greater or Equal
//
// C version



int main()
{

      int x=3;
      int y=5;
      int z=0;

      if(x >= y)
         z=x;
}
```

```
; If Greater or Equal
;
; Assembly version

.data
x       BYTE    3
y       BYTE    5
z       BYTE    0

.code
        LOAD  A, [x]
        LOAD  B, [y]
        CMP   B, A          ; these are swapped
        BRG   End
        STORE [z], A
End:    NOOP
```

C vs. Assembly

```
// If Greater or Equal
//
// C version



int main()
{

      int x=3;
      int y=5;
      int z=0;

      if(y <= x)
         z=x;
}
```

```
; If Greater or Equal
;
; Assembly version

.data
x       BYTE    3
y       BYTE    5
z       BYTE    0

.code
        LOAD   A, [x]
        LOAD   B, [y]
        CMP    B, A          ; these are swapped
        BRG    End
        STORE  [z], A
End:    NOOP
```

C vs. Assembly

```
// If Greater or Equal
//
// C version



int main()
{

      int x=3;
      int y=5;
      int z=0;

      if(y <= x)
         z=x;
}
```

```
; If Greater or Equal
;
; Assembly version

.data
x       BYTE    3
y       BYTE    5
z       BYTE    0

.code
        LOAD   A, [x]
        LOAD   B, [y]
        CMP    B, A          ; these are swapped
        BRG    End
        STORE  [z], A
End:    NOOP
```

instead of y <= x,
check if y > x

If Greater

C vs. Assembly

```
// If Greater
//
// C version



int main()
{

      int x=3;
      int y=5;
      int z=0;

      if(x > y)
         z=x;
}
```

```
; If Greater
;
; Assembly version

.data
x       BYTE    3
y       BYTE    5
z       BYTE    0

.code
        LOAD  A, [x]
        LOAD  B, [y]
        CMP   B, A        ; these are swapped
        BRGE  End
        STORE [z], A
End:    NOOP
```

C vs. Assembly

```c
// If Greater
//
// C version



int main()
{

      int x=3;
      int y=5;
      int z=0;

      if(y < x)
         z=x;
}
```

```
; If Greater
;
; Assembly version

.data
x       BYTE    3
y       BYTE    5
z       BYTE    0

.code
        LOAD   A, [x]
        LOAD   B, [y]
        CMP    B, A        ; these are swapped
        BRGE   End
        STORE  [z], A
End:    NOOP
```

C vs. Assembly

```c
// If Greater
//
// C version



int main()
{

      int x=3;
      int y=5;
      int z=0;

      if(y < x)
         z=x;
}
```

```
; If Greater
;
; Assembly version

.data
x       BYTE    3
y       BYTE    5
z       BYTE    0

.code
        LOAD   A, [x]
        LOAD   B, [y]
        CMP    B, A          ; these are swapped
        BRGE   End
        STORE [z], A
End:    NOOP
```

instead of y < x,
check if y >= x

Common Comparisons

```
(x < y)
CMP x,y
BRGE End
```

```
(x <= y)
CMP x,y
BRG End
```

```
(x == y)
CMP x,y
BRNE End
```

```
(x!= y)
CMP x,y
BRE End
```

~~(x >= y)~~

```
CMP x,y
BRL End
```

```
CMP y,x
BRG End
```

~~(x > y)~~

```
CMP x,y
BRLE End
```

```
CMP y,x
BRGE End
```

If Statement:
Comparison of Unsigned Numbers

(not supported by this CPU)

Comparison of Signed Numbers

- Equal — ZF
- Not equal — $\overline{ZF}$
- Greater — $\overline{ZF} \bullet XNOR(NF, OF)$
- Greater or Equal — $XNOR(NF, OF)$
- Less — $XOR(NF, OF)$
- Less or Equal — $ZF + XOR(NF, OF)$

Comparison of Unsigned Numbers

- Equal — ZF
- Not equal — $\overline{ZF}$
- Above — $\overline{ZF} \cdot CF$
- Above or Equal — CF
- Below — $\overline{CF}$
- Below or Equal — $ZF + \overline{CF}$

Signed v.s. Unsigned

- Equal ZF
- Not equal $\overline{ZF}$
- Greater $\overline{ZF}$ • XNOR(NF, OF)
- Greater or Equal XNOR(NF, OF)
- Less XOR(NF, OF)
- Less or Equal ZF + XOR(NF, OF)

- Equal ZF
- Not equal $\overline{ZF}$
- Above $\overline{ZF}$ • CF
- Above or Equal CF
- Below $\overline{CF}$
- Below or Equal ZF + $\overline{CF}$

Signed v.s. Unsigned

they overlap only here

Signed		Unsigned	
• Equal	ZF	• Equal	ZF
• Not equal	$\overline{ZF}$	• Not equal	$\overline{ZF}$
• Greater	$\overline{ZF}$ • XNOR(NF, OF)	• Above	$\overline{ZF}$ • CF
• Greater or Equal	XNOR(NF, OF)	• Above or Equal	CF
• Less	XOR(NF, OF)	• Below	$\overline{CF}$
• Less or Equal	ZF + XOR(NF, OF)	• Below or Equal	ZF + $\overline{CF}$

Signed v.s. Unsigned

BRE	BRanch if Equal
BRZ	BRanch if Zero
BRNE	BRanch if Not Equal
BRNZ	BRanch if Not Zero
BRG	BRanch if Greater
BRGE	BRanch if Greater than or Equal
BRL	BRanch if Less
BRLE	BRanch if Less than or Equal

BRE	Ranch if Equal
BRZ	BRanch if Zero
BRNE	BRanch if Not Equal
BRNZ	BRanch if Not Zero
BRA	BRanch if Above
BRAE	BRanch if Above or Equal
BRB	BRanch if Below
BRBE	BRanch if Below or Equal

Signed v.s. Unsigned

BRE	BRanch if Equal
BRZ	BRanch if Zero
BRNE	BRanch if Not Equal
BRNZ	BRanch if Not Zero
BRG	BRanch if Greater
BRGE	BRanch if Greater than or Equal
BRL	BRanch if Less
BRLE	BRanch if Less than or Equal

BRE	Ranch if Equal
BRZ	BRanch if Zero
BRNE	BRanch if Not Equal
BRNZ	BRanch if Not Zero
BRA	BRanch if Above
BRAE	BRanch if Above or Equal
BRB	BRanch if Below
BRBE	BRanch if Below or Equal

The OPCODEs in blue are NOT implemented on this CPU

Thus, comparing unsigned numbers requires adding new OPCODEs

BRE	Ranch if Equal
BRZ	BRanch if Zero
BRNE	BRanch if Not Equal
BRNZ	BRanch if Not Zero
BRA	BRanch if Above
BRAE	BRanch if Above or Equal
BRB	BRanch if Below
BRBE	BRanch if Below or Equal

Thus, comparing unsigned numbers requires adding new OPCODEs

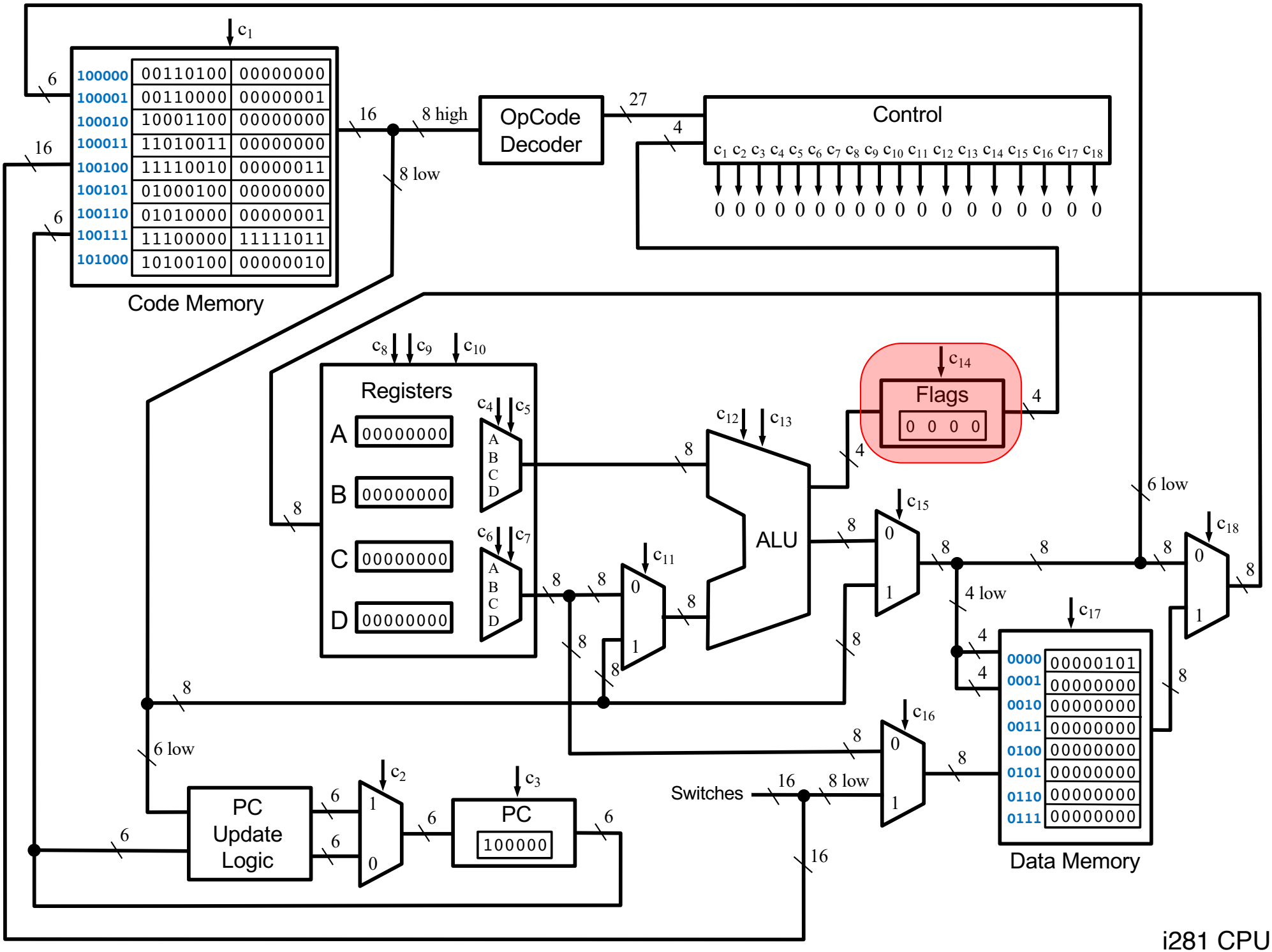
BRE	Ranch if Equal
BRZ	BRanch if Zero
BRNE	BRanch if Not Equal
BRNZ	BRanch if Not Zero
BRA	BRanch if Above
BRAE	BRanch if Above or Equal
BRB	BRanch if Below
BRBE	BRanch if Below or Equal

at a minimum you need only these two

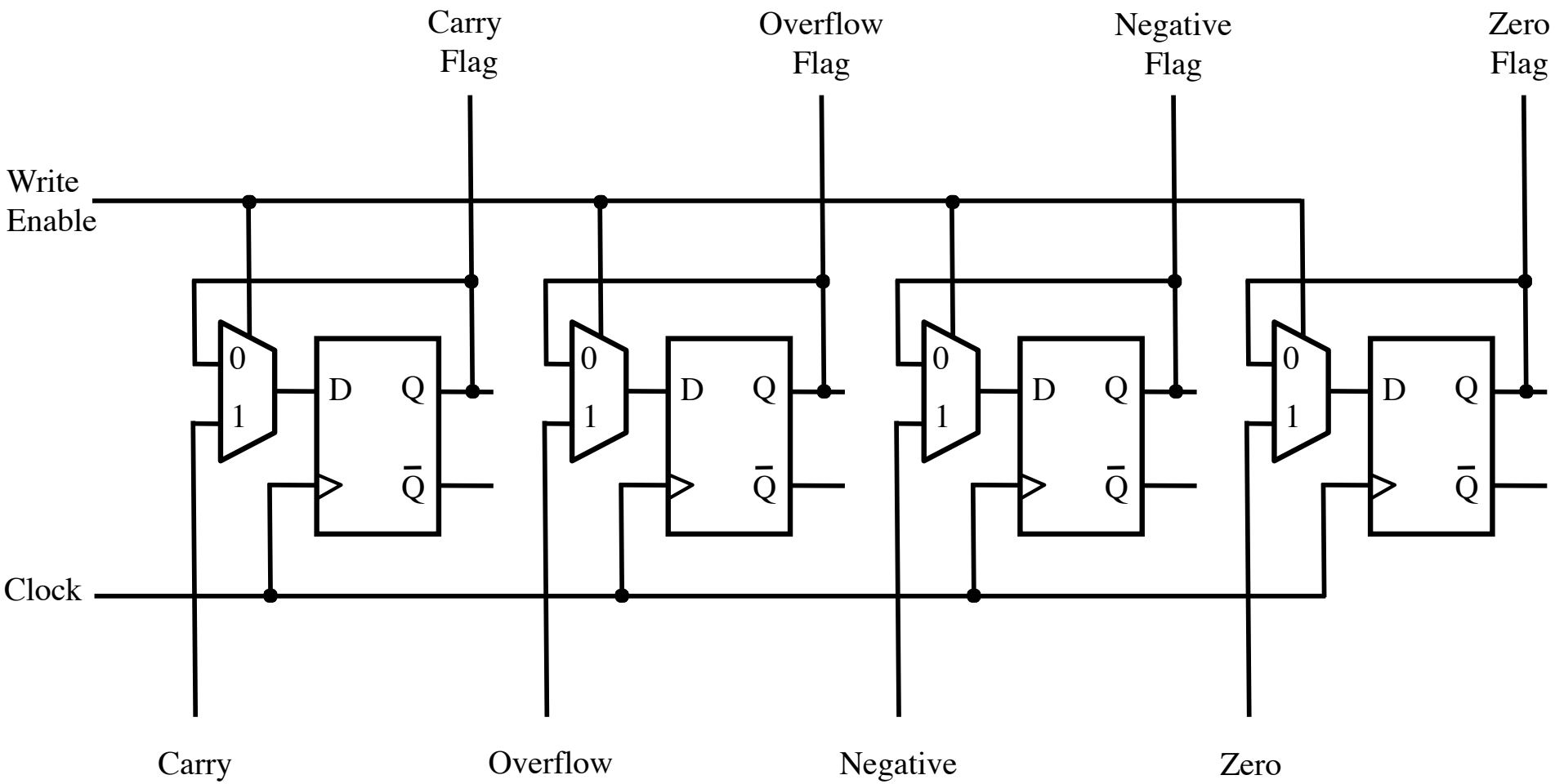
Thus, comparing unsigned numbers requires adding new OPCODEs

	BRE	Ranch if Equal
	BRZ	BRanch if Zero
	BRNE	BRanch if Not Equal
	BRNZ	BRanch if Not Zero
	BRA	BRanch if Above
	BRAE	BRanch if Above or Equal
or these two	BRB	BRanch if Below
or these two	BRBE	BRanch if Below or Equal

OPCODEs that check the Flags


c1
6
100000 00110100 00000000
100001 00110000 00000001
100010 10001100 00000000
100011 11010011 00000000
100100 11110010 00000011
100101 01000100 00000000
100110 01010000 00000001
100111 11100000 11111011
101000 10100100 00000010
Code Memory
16
8 high
8 low
OpCode Decoder
27
4
Control
c1 c2 c3 c4 c5 c6 c7 c8 c9 c10 c11 c12 c13 c14 c15 c16 c17 c18
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
c8 c9 c10
Registers
A 00000000
B 00000000
C 00000000
D 00000000
c4 c5
c6 c7
A B C D
c14
Flags
0 0 0 0
4
c12 c13
ALU
c11
c15
c16
c18
6 low
4 low
c17
0000 00000101
0001 00000000
0010 00000000
0011 00000000
0100 00000000
0101 00000000
0110 00000000
0111 00000000
Data Memory
Switches
16
8 low
PC Update Logic
c2
c3
PC
100000
i281 CPU

The Flags Register



You could also add OPCODEs that just check a specific flag

```
BRC         BRanch if Carry
BRNC        BRanch if No Carry

BRO         BRanch if Overflow
BRNO        BRanch if No Overflow

BRN         BRanch if Negative
BRNN        BRanch if Not Negative

BRZ         BRanch if Zero
BRNZ        BRanch if Not Zero
```

only these two are currently supported

You could also add OPCODEs that just check a specific flag

BRC	BRanch if Carry
BRNC	BRanch if No Carry
BRO	BRanch if Overflow
BRNO	BRanch if No Overflow
BRN	BRanch if Negative
BRNN	BRanch if Not Negative
BRZ	BRanch if Zero
BRNZ	BRanch if Not Zero

BRE
BRNE

equivalent to

You could also add OPCODEs that just check a specific flag

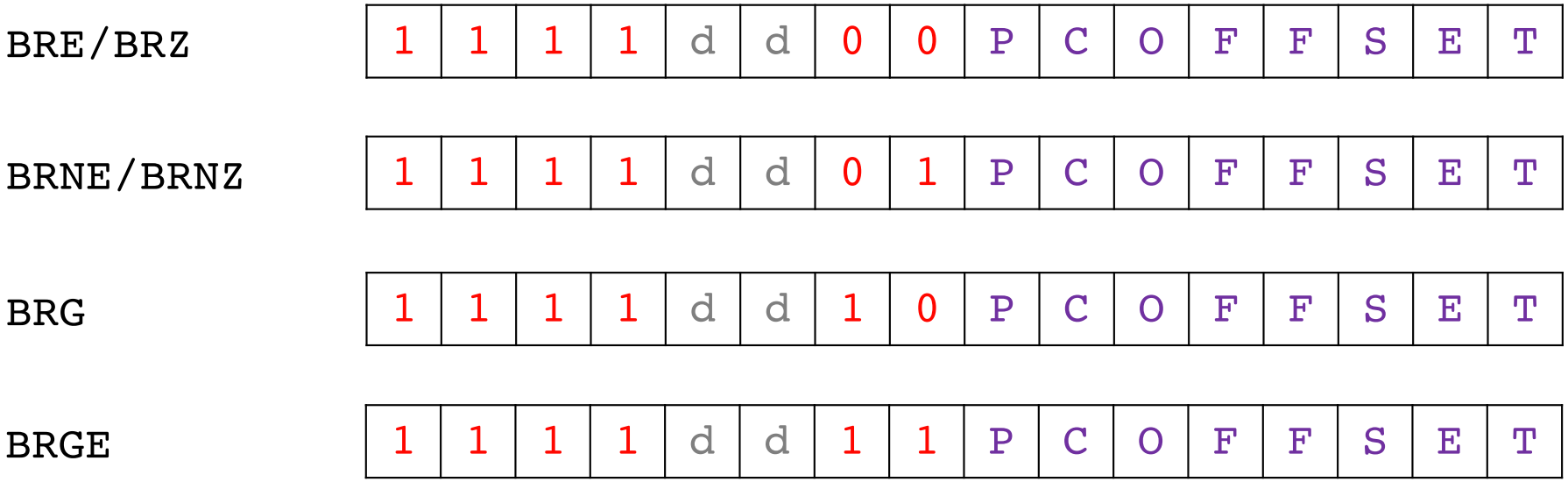
		equivalent to
BRC	BRanch if Carry	BRAE
BRNC	BRanch if No Carry	BRB
BRO	BRanch if Overflow	
BRNO	BRanch if No Overflow	
BRN	BRanch if Negative	
BRNN	BRanch if Not Negative	
BRZ	BRanch if Zero	
BRNZ	BRanch if Not Zero	

Signed v.s. Unsigned

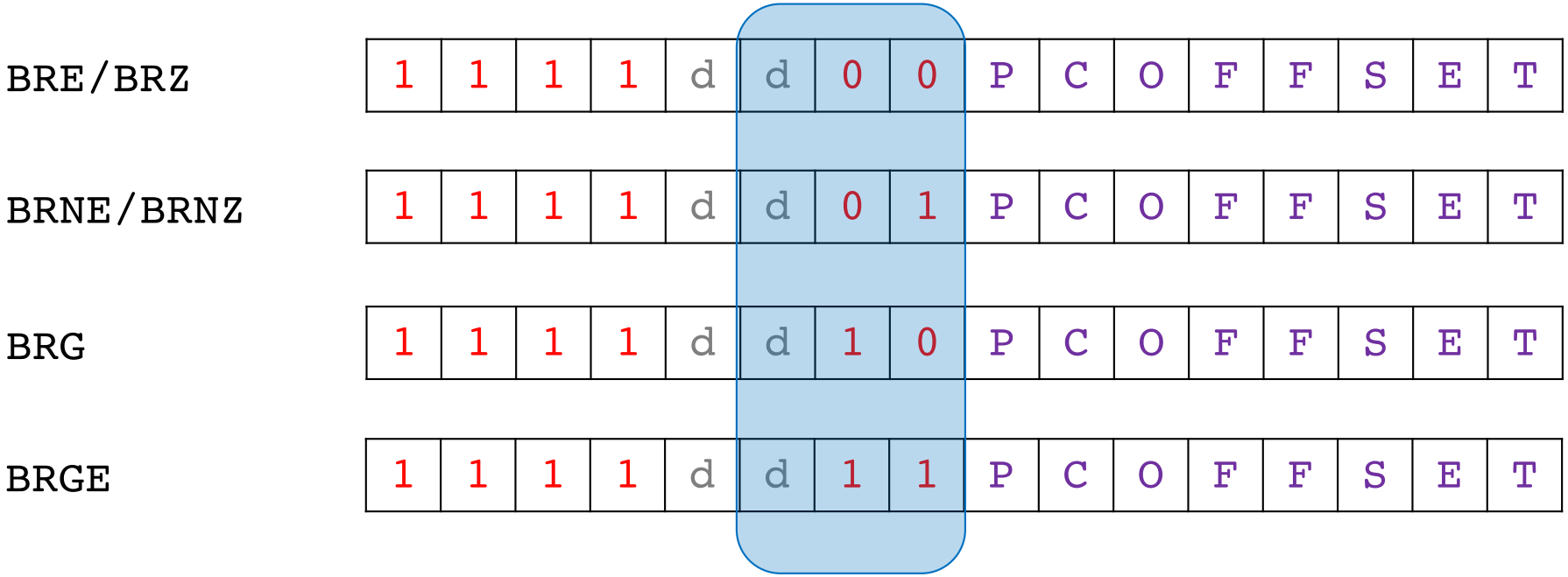
- Equal ZF
- Not equal $\overline{ZF}$
- Greater $\overline{ZF} \cdot XNOR(NF, OF)$
- Greater or Equal $XNOR(NF, OF)$
- Less $XOR(NF, OF)$
- Less or Equal $ZF + XOR(NF, OF)$

- Equal ZF
- Not equal $\overline{ZF}$
- Above $\overline{ZF} \cdot CF$
- Above or Equal CF
- Below $\overline{CF}$
- Below or Equal $ZF + \overline{CF}$

How to add more BRanch OpCODEs

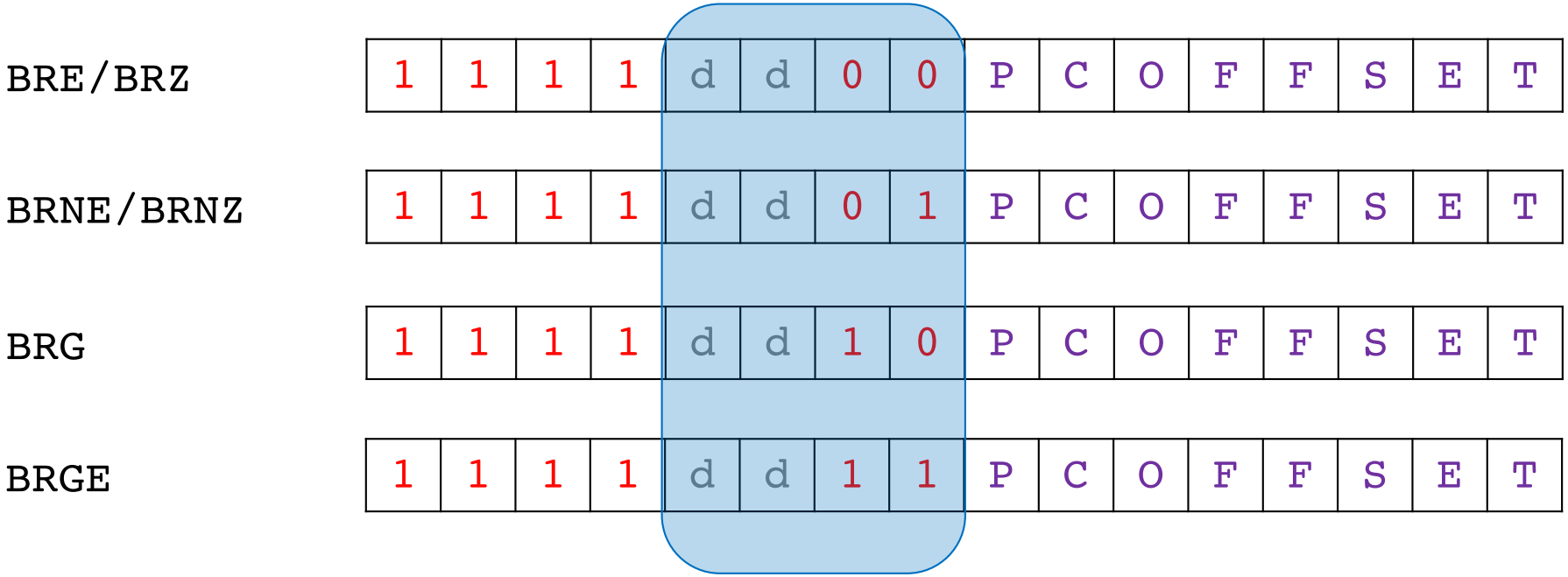


How to add more BRanch OpCODES

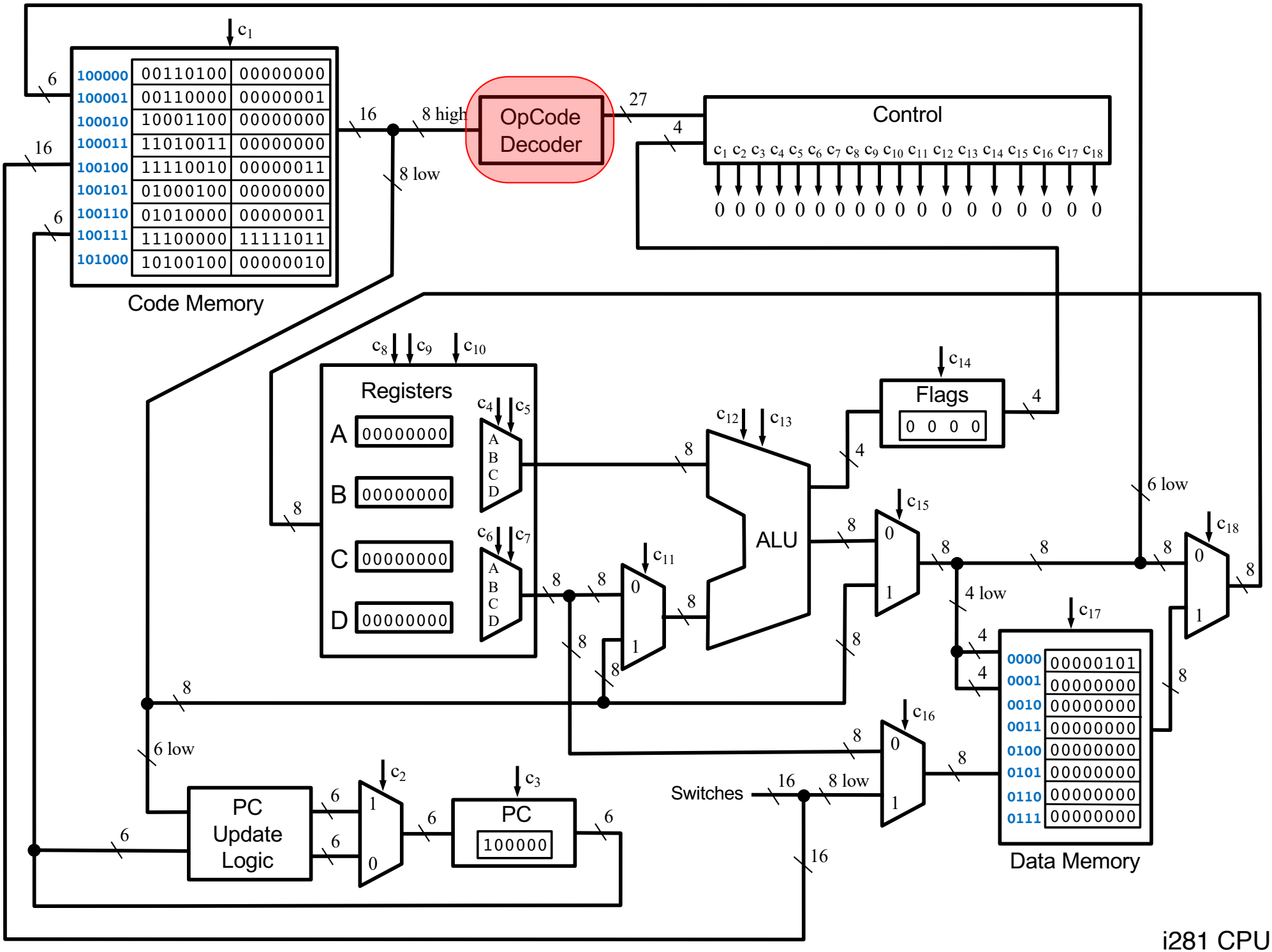


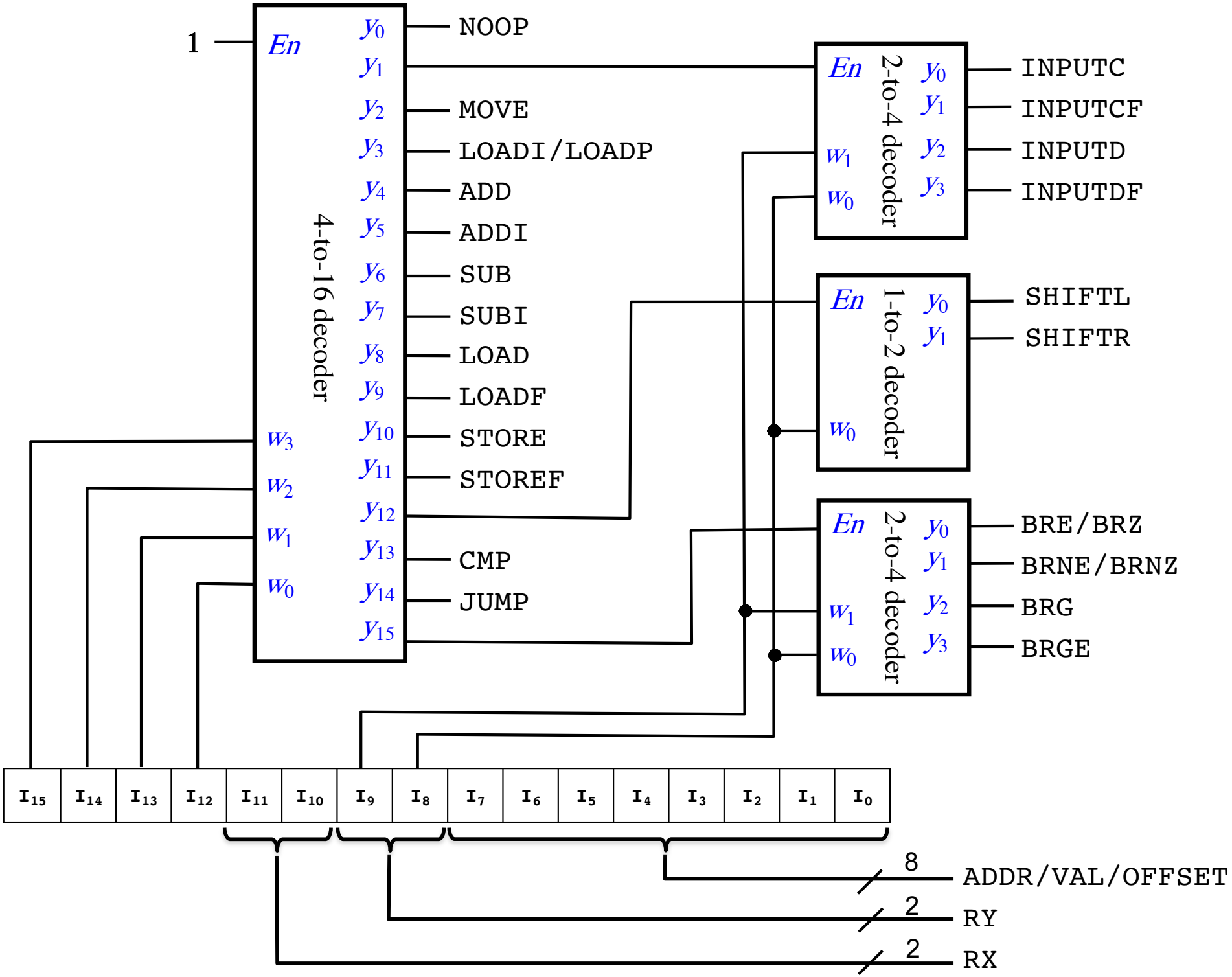
could use this don't care bit and
update the OpCODE decoder

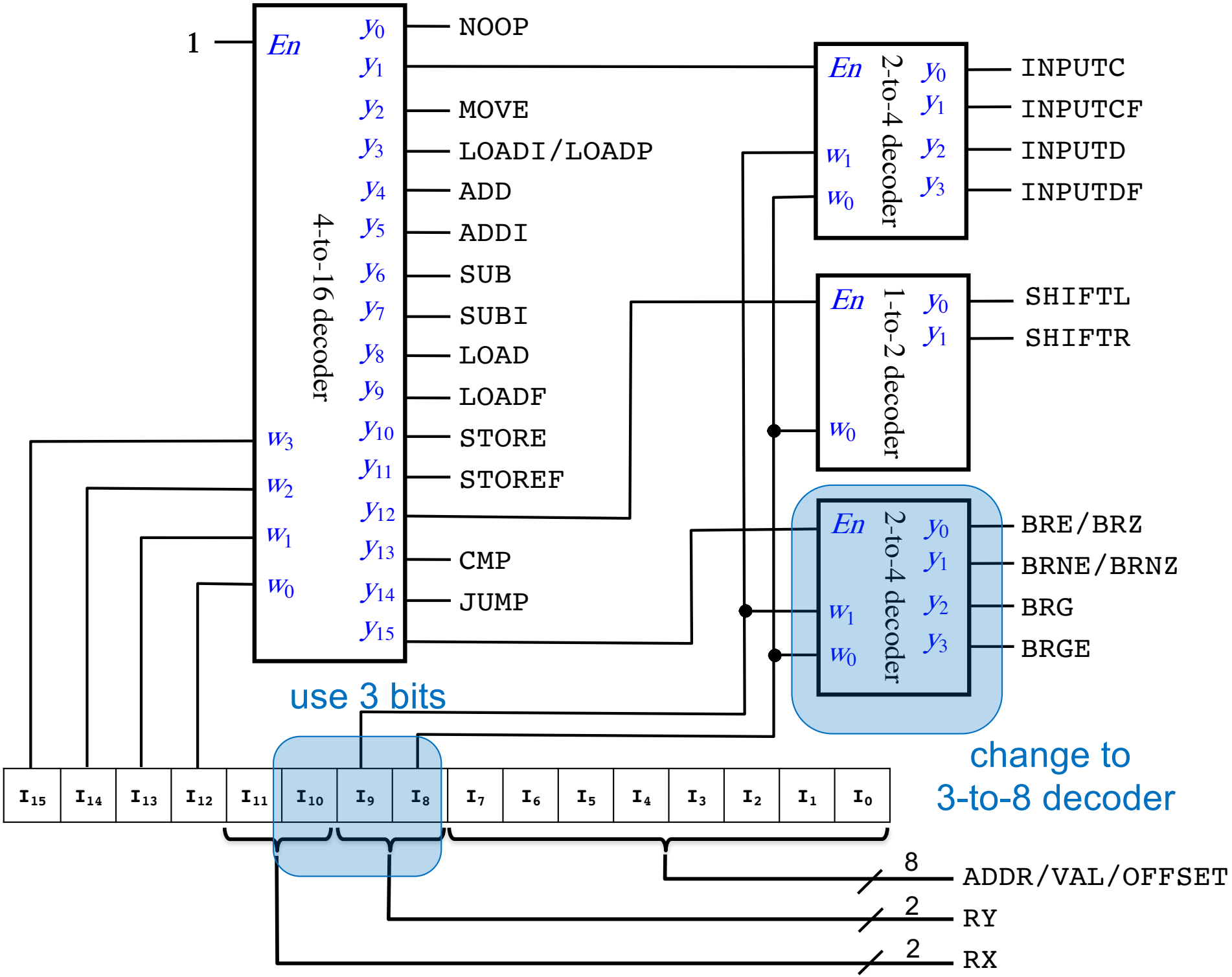
How to add more BRanch OpCODES

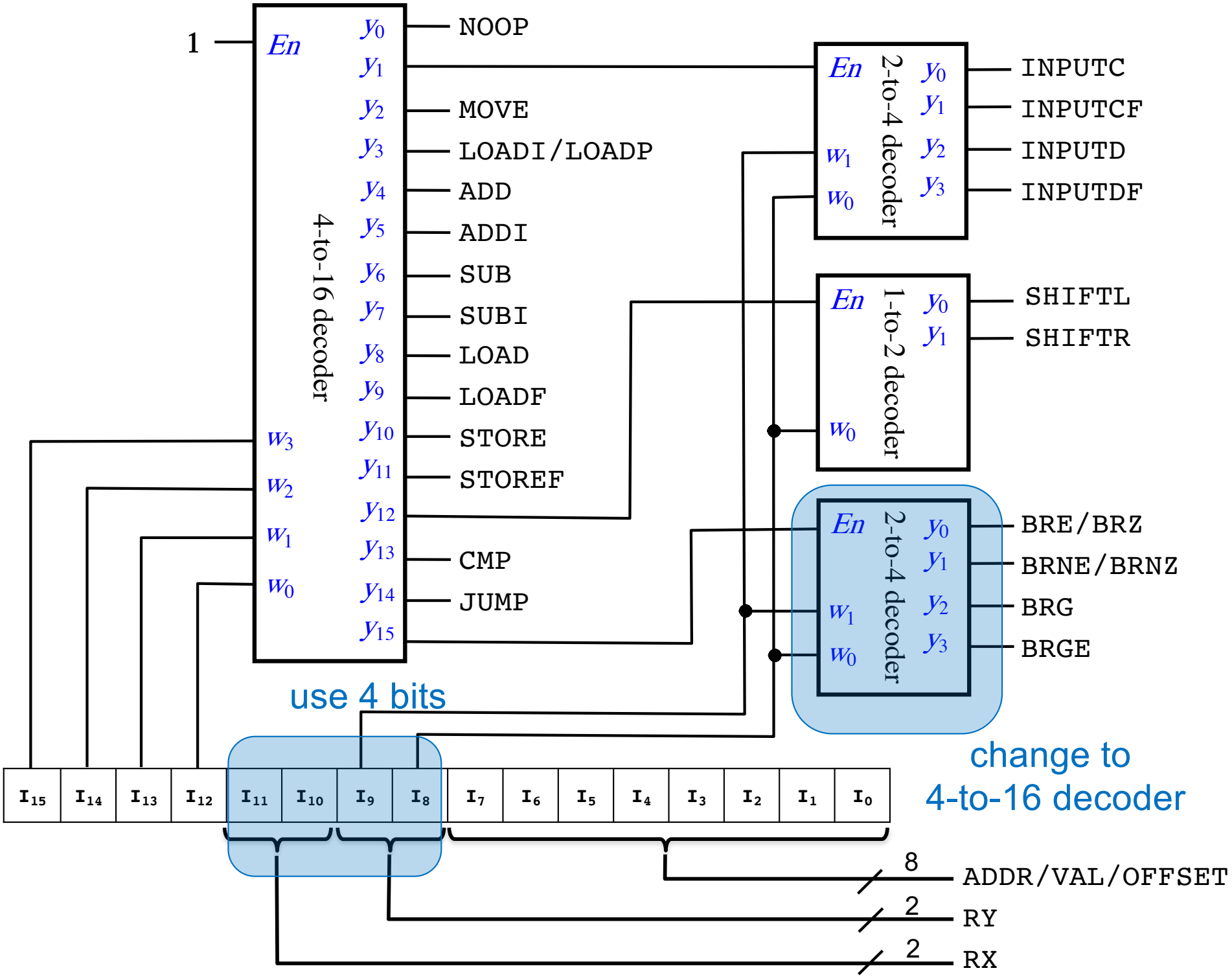


could use these two don't care bits and
update the OpCODE decoder


c1
6
100000 00110100 00000000
100001 00110000 00000001
100010 10001100 00000000
100011 11010011 00000000
100100 11110010 00000011
100101 01000100 00000000
100110 01010000 00000001
100111 11100000 11111011
101000 10100100 00000010
Code Memory
16
8 high
8 low
OpCode Decoder
27
4
Control
c1 c2 c3 c4 c5 c6 c7 c8 c9 c10 c11 c12 c13 c14 c15 c16 c17 c18
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
c8 c9 c10
Registers
A 00000000
B 00000000
C 00000000
D 00000000
c4 c5
c6 c7
A B C D
8
c12 c13
ALU
c14
Flags
0 0 0 0
4
c15
c11
c16
c18
c17
6 low
4 low
0000 00000101
0001 00000000
0010 00000000
0011 00000000
0100 00000000
0101 00000000
0110 00000000
0111 00000000
Data Memory
Switches
16
8 low
PC Update Logic
c2
c3
PC
100000
6
i281 CPU


1
En
4-to-16 decoder
y_0
y_1
y_2
y_3
y_4
y_5
y_6
y_7
y_8
y_9
y_{10}
y_{11}
y_{12}
y_{13}
y_{14}
y_{15}
w_3
w_2
w_1
w_0
NOOP
MOVE
LOADI/LOADP
ADD
ADDI
SUB
SUBI
LOAD
LOADF
STORE
STOREF
CMP
JUMP
2-to-4 decoder
INPUTC
INPUTCF
INPUTD
INPUTDF
1-to-2 decoder
SHIFTL
SHIFTR
BRE/BRZ
BRNE/BRNZ
BRG
BRGE
I_{15} I_{14} I_{13} I_{12} I_{11} I_{10} I_9 I_8 I_7 I_6 I_5 I_4 I_3 I_2 I_1 I_0
8
ADDR/VAL/OFFSET
2
RY
2
RX


1
En
4-to-16 decoder
y_0 NOOP
y_1
y_2 MOVE
y_3 LOADI/LOADP
y_4 ADD
y_5 ADDI
y_6 SUB
y_7 SUBI
y_8 LOAD
y_9 LOADF
y_{10} STORE
y_{11} STOREF
y_{12}
y_{13} CMP
y_{14} JUMP
y_{15}
w_3
w_2
w_1
w_0
En
2-to-4 decoder
y_0 INPUTC
y_1 INPUTCF
y_2 INPUTD
y_3 INPUTDF
w_1
w_0
En
1-to-2 decoder
y_0 SHIFTL
y_1 SHIFTR
w_0
En
2-to-4 decoder
y_0 BRE/BRZ
y_1 BRNE/BRNZ
y_2 BRG
y_3 BRGE
w_1
w_0
use 3 bits
change to
3-to-8 decoder
I_{15} I_{14} I_{13} I_{12} I_{11} I_{10} I_9 I_8 I_7 I_6 I_5 I_4 I_3 I_2 I_1 I_0
8 ADDR/VAL/OFFSET
2 RY
2 RX


1
En
4-to-16 decoder
y_0 NOOP
y_1
y_2 MOVE
y_3 LOADI/LOADP
y_4 ADD
y_5 ADDI
y_6 SUB
y_7 SUBI
y_8 LOAD
y_9 LOADF
y_{10} STORE
y_{11} STOREF
y_{12}
y_{13} CMP
y_{14} JUMP
y_{15}
w_3
w_2
w_1
w_0
En
2-to-4 decoder
y_0 INPUTC
y_1 INPUTCF
y_2 INPUTD
y_3 INPUTDF
w_1
w_0
En
1-to-2 decoder
y_0 SHIFTL
y_1 SHIFTR
w_0
En
2-to-4 decoder
y_0 BRE/BRZ
y_1 BRNE/BRNZ
y_2 BRG
y_3 BRGE
w_1
w_0
use 4 bits
change to
4-to-16 decoder
I_{15} I_{14} I_{13} I_{12} I_{11} I_{10} I_9 I_8 I_7 I_6 I_5 I_4 I_3 I_2 I_1 I_0
8 ADDR/VAL/OFFSET
2 RY
2 RX

If-Else Statement

C vs. Assembly

```c
// If-Else Statement
//
// C version


int main()
{

      int x=3;
      int y=5;
      int z;

      if (x<y)
        z=x;
      else
        z=y;
}
```

```
; If If-Else Statement
;
; Assembly version

.data
x       BYTE    3
y       BYTE    5
z       BYTE    ?

.code
        LOAD  A, [x]
        LOAD  B, [y]
If:     CMP   A, B
        BRGE  Else
        STORE [z], A
        JUMP  End
Else:   STORE [z], B
End:    NOOP
```

If with two conditions (OR)

C vs. Assembly

```c
// If with 2 conditions (OR)
//
// C version


int main()
{

   int x=9;
   int min=1;
   int max=8;
   int inRange=1;

   if ( (x<min) || (x>max) )
         inRange=0;
}
```

```
; Assembly version

.data
x         BYTE     9
min       BYTE     1
max       BYTE     8
inRange   BYTE     1

.code
          LOAD  A, [x]
          LOAD  B, [min]
          LOAD  C, [max]
First:    CMP   A, B              ; x < min ?
          BRGE  Second
Set:      LOADI D, 0
          STORE [inRange], D
          JUMP  End
Second:   CMP   C, A               ; max < x ?
          BRGE  End
          JUMP  Set
End:      NOOP
```

C vs. Assembly

```c
// If with 2 conditions (OR)
// this is closer to assembly
int main()
{
   int x=9;
   int min=1;
   int max=8;
   int inRange=1;

   if(x < min)     // First
   {
     Set:
       inRange=0;
       goto End;
   }
   else if(max < x) // Second
                    // swapped condition
   {
      goto Set;
   }

  End:
}
```

```
; Assembly version

.data
x         BYTE     9
min       BYTE     1
max       BYTE     8
inRange   BYTE     1

.code
          LOAD   A, [x]
          LOAD   B, [min]
          LOAD   C, [max]
First:    CMP    A, B              ; x < min ?
          BRGE   Second
Set:      LOADI  D, 0
          STORE  [inRange], D
          JUMP   End
Second:   CMP    C, A               ; max < x ?
          BRGE   End
          JUMP   Set
End:      NOOP
```

C vs. Assembly

```c
// If with 2 conditions (OR)
// this is closer to assembly
int main()
{
   int x=9;
   int min=1;
   int max=8;
   int inRange=1;

   if(x < min)     // First
   {
     Set:
       inRange=0;
       goto End;
   }
   else if(max < x) // Second
   {
      goto Set;
   }

  End:
}
```

```
; Assembly version

.data
x         BYTE     9
min       BYTE     1
max       BYTE     8
inRange   BYTE     1

.code
          LOAD   A, [x]
          LOAD   B, [min]
          LOAD   C, [max]
First:    CMP    A, B
          BRGE   Second
Set:      LOADI  D, 0
          STORE  [inRange], D
          JUMP   End
Second:   CMP    C, A              ; max < x ?
          BRGE   End
          JUMP   Set
End:      NOOP
```

instead of x < min,
check if x >= min

C vs. Assembly

```c
// If with 2 conditions (OR)
// this is closer to assembly
int main()
{
   int x=9;
   int min=1;
   int max=8;
   int inRange=1;

   if(x < min)     // First
   {
     Set:
       inRange=0;
       goto End;
   }
   else if(max < x) // Second
   {
      goto Set;
   }

  End:
}
```

```
; Assembly version

.data
x         BYTE     9
min       BYTE     1
max       BYTE     8
inRange   BYTE     1

.code
          LOAD   A, [x]
          LOAD   B, [min]
          LOAD   C, [max]
First:    CMP    A, B
          BRGE   Second
Set:      LOADI  D, 0
          STORE  [inRange], D
          JUMP   End
Second:   CMP    C, A
          BRGE   End
          JUMP   Set
End:      NOOP
```

instead of max < x,
check if max >= x

If with two conditions (AND)

C vs. Assembly

```c
// If with 2 conditions (AND)
//
// C version


int main()
{

   int x=5;
   int min=1;
   int max=8;
   int inRange=0;

   if ( (x>=min) && (x<=max) )
        inRange=1;
}
```

```
; Assembly version


.data
x         BYTE     5
min       BYTE     1
max       BYTE     8
inRange   BYTE     0

.code
          LOAD   A, [x]
          LOAD   B, [min]
          LOAD   C, [max]
          CMP    B, A            ; min <= x ?
          BRG    End
          CMP    A, C            ; x <= max ?
          BRG    End
          LOADI  D, 1
          STORE  [inRange], D
End:      NOOP
```

C vs. Assembly

```c
// If with 2 conditions (AND)
//
// C version


int main()
{
   int x=5;
   int min=1;
   int max=8;
   int inRange=0;

   if(min<=x)  // swapped dir.
   {
       if(x<=max)
       {
          inRange=1;
       }
    }
 }
```

```
; Assembly version


.data
x         BYTE     5
min       BYTE     1
max       BYTE     8
inRange   BYTE     0

.code
          LOAD   A, [x]
          LOAD   B, [min]
          LOAD   C, [max]
          CMP    B, A              ; min <= x ?
          BRG    End
          CMP    A, C              ; x <= max ?
          BRG    End
          LOADI  D, 1
          STORE  [inRange], D
End:      NOOP
```

C vs. Assembly

```c
// If with 2 conditions (AND)
//
// C version


int main()
{
   int x=5;
   int min=1;
   int max=8;
   int inRange=0;

   if(min<=x)  // swapped dir.
   {
       if(x<=max)
       {
          inRange=1;
       }
    }
 }
```

```
; Assembly version

.data
x         BYTE     5
min       BYTE     1
max       BYTE     8
inRange   BYTE     0

.code
          LOAD   A, [x]
          LOAD   B, [min]
          LOAD   C, [max]
          CMP    B, A
          BRG    End
          CMP    A, C          ; x <= max ?
          BRG    End
          LOADI  D, 1
          STORE  [inRange], D
End:      NOOP
```

instead of min <= x,
check if min > x

C vs. Assembly

```c
// If with 2 conditions (AND)
//
// C version


int main()
{
   int x=5;
   int min=1;
   int max=8;
   int inRange=0;

   if(min<=x)  // swapped dir.
   {
       if(x<=max)
       {
          inRange=1;
       }
    }
 }
```

```
; Assembly version

.data
x         BYTE     5
min       BYTE     1
max       BYTE     8
inRange   BYTE     0

.code
          LOAD   A, [x]
          LOAD   B, [min]
          LOAD   C, [max]
          CMP    B, A
          BRG    End
          CMP    A, C
          BRG    End
          LOADI  D, 1
          STORE  [inRange], D
End:      NOOP
```

instead of x <= max,
check if x > max

Switch Statement

C vs. Assembly

```c
// Switch Statement
//
// C version

int main()
{

     int x=6;
     int y;

     switch(x)
     {
        case 0:        y=2*x;
                       break;

        case 1:        y=x+3;
                       break;

        case 2:        y=x-1;
                       break;

        default:       y=x/2;
                       break;
     }
}
```

```
; Assembly version
.data
x          BYTE         6
y          BYTE         ?

.code
           LOAD    A, [x]
Zero:      LOADI   C, 0
           CMP     A, C
           BRNE    One
           MOVE    B, A
           SHIFTL  B
           JUMP    End
One:       LOADI   C, 1
           CMP     A, C
           BRNE    Two
           MOVE    B, A
           ADDI    B, 3
           JUMP    End
Two:       LOADI   C, 2
           CMP     A, C
           BRNE    Default
           MOVE    B, A
           SUBI    B, 1
           JUMP    End
Default:   MOVE    B, A
           SHIFTR  B
End:       STORE   [y], B
           NOOP
```

C vs. Assembly

```c
// Switch Statement
//
// C version

int main()
{

      int x=6;
      int y;

      switch(x)
      {
         case 0:        y=2*x;
                        break;

         case 1:        y=x+3;
                        break;

         case 2:        y=x-1;
                        break;

         default:       y=x/2;
                        break;

      }
}
```

```
; Assembly version
.data
x           BYTE          6
y           BYTE          ?

.code
            LOAD    A, [x]
Zero:       LOADI   C, 0
            CMP     A, C
            BRNE    One
            MOVE    B, A
            SHIFTL  B
            JUMP    End
One:        LOADI   C, 1
            CMP     A, C
            BRNE    Two
            MOVE    B, A
            ADDI    B, 3
            JUMP    End
Two:        LOADI   C, 2
            CMP     A, C
            BRNE    Default
            MOVE    B, A
            SUBI    B, 1
            JUMP    End
Default:    MOVE    B, A
            SHIFTR  B
End:        STORE   [y], B
            NOOP
```

C vs. Assembly

```c
// Switch Statement
//
// C version

int main()
{

      int x=6;
      int y;

      switch(x)
      {
         case 0:        y=2*x;
                        break;

         case 1:        y=x+3;
                        break;

         case 2:        y=x-1;
                        break;

         default:       y=x/2;
                        break;

      }
}
```

```
; Assembly version
.data
x           BYTE          6
y           BYTE          ?

.code
            LOAD    A, [x]
Zero:       LOADI   C, 0
            CMP     A, C
            BRNE    One
            MOVE    B, A
            SHIFTL  B
            JUMP    End
One:        LOADI   C, 1
            CMP     A, C
            BRNE    Two
            MOVE    B, A
            ADDI    B, 3
            JUMP    End
Two:        LOADI   C, 2
            CMP     A, C
            BRNE    Default
            MOVE    B, A
            SUBI    B, 1
            JUMP    End
Default:    MOVE    B, A
            SHIFTR  B
End:        STORE   [y], B
            NOOP
```

C vs. Assembly

```c
// Switch Statement
//
// C version

int main()
{

     int x=6;
     int y;

     switch(x)
     {
        case 0:        y=2*x;
                       break;

        case 1:        y=x+3;
                       break;

        case 2:        y=x-1;
                       break;

        default:       y=x/2;
                       break;
     }
}
```

```
; Assembly version
.data
x          BYTE         6
y          BYTE         ?

.code
           LOAD    A, [x]
Zero:      LOADI   C, 0
           CMP     A, C
           BRNE    One
           MOVE    B, A
           SHIFTL  B
           JUMP    End
One:       LOADI   C, 1
           CMP     A, C
           BRNE    Two
           MOVE    B, A
           ADDI    B, 3
           JUMP    End
Two:       LOADI   C, 2
           CMP     A, C
           BRNE    Default
           MOVE    B, A
           SUBI    B, 1
           JUMP    End
Default:   MOVE    B, A
           SHIFTR  B
End:       STORE   [y], B
           NOOP
```

C vs. Assembly

```
// Switch Statement
//
// C version

int main()
{

      int x=6;
      int y;

      switch(x)
      {
          case 0:        y=2*x;
                         break;

          case 1:        y=x+3;
                         break;

          case 2:        y=x-1;
                         break;

          default:       y=x/2;
                         break;

      }
}
```

```
; Assembly version
.data
x           BYTE          6
y           BYTE          ?

.code
            LOAD    A, [x]
Zero:       LOADI   C, 0
            CMP     A, C
            BRNE    One
            MOVE    B, A
            SHIFTL  B
            JUMP    End
One:        LOADI   C, 1
            CMP     A, C
            BRNE    Two
            MOVE    B, A
            ADDI    B, 3
            JUMP    End
Two:        LOADI   C, 2
            CMP     A, C
            BRNE    Default
            MOVE    B, A
            SUBI    B, 1
            JUMP    End
Default:    MOVE    B, A
            SHIFTR  B
End:        STORE   [y], B
            NOOP
```

C vs. Assembly

```c
// Switch Statement
//
// C version

int main()
{

      int x=6;
      int y;

      switch(x)
      {
         case 0:        y=2*x;
                        break;

         case 1:        y=x+3;
                        break;

         case 2:        y=x-1;
                        break;

         default:       y=x/2;
                        break;
      }
}
```

```
; Assembly version
.data
x           BYTE          6
y           BYTE          ?

.code
            LOAD    A, [x]
Zero:       LOADI   C, 0
            CMP     A, C
            BRNE    One
            MOVE    B, A
            SHIFTL  B
            JUMP    End
One:        LOADI   C, 1
            CMP     A, C
            BRNE    Two
            MOVE    B, A
            ADDI    B, 3
            JUMP    End
Two:        LOADI   C, 2
            CMP     A, C
            BRNE    Default
            MOVE    B, A
            SUBI    B, 1
            JUMP    End
Default:    MOVE    B, A
            SHIFTR  B
End:        STORE   [y], B
            NOOP
```

C vs. Assembly

```c
// Switch Statement
//
// C version

int main()
{

     int x=6;
     int y;

     switch(x)
     {
        case 0:        y=2*x;
                       break;

        case 1:        y=x+3;
                       break;

        case 2:        y=x-1;
                       break;

        default:       y=x/2;
                       break;
     }
}
```

```
; Assembly version
.data
x          BYTE          6
y          BYTE          ?

.code
           LOAD     A, [x]
Zero:      LOADI    C, 0
           CMP      A, C
           BRNE     One
           MOVE     B, A
           SHIFTL   B
           JUMP     End
One:       LOADI    C, 1
           CMP      A, C
           BRNE     Two
           MOVE     B, A
           ADDI     B, 3
           JUMP     End
Two:       LOADI    C, 2
           CMP      A, C
           BRNE     Default
           MOVE     B, A
           SUBI     B, 1
           JUMP     End
Default:   MOVE     B, A
           SHIFTR   B
End:       STORE    [y], B
           NOOP
```

C vs. Assembly

```c
// Switch Statement
//
// C version

int main()
{

      int x=6;
      int y;

      switch(x)
      {
         case 0:        y=2*x;
                        break;

         case 1:        y=x+3;
                        break;

         case 2:        y=x-1;
                        break;

         default:       y=x/2;
                        break;
      }
}
```

```
; Assembly version
.data
x           BYTE          6
y           BYTE          ?

.code
            LOAD    A, [x]
Zero:       LOADI   C, 0
            CMP     A, C
            BRNE    One
            MOVE    B, A
            SHIFTL  B
            JUMP    End
One:        LOADI   C, 1
            CMP     A, C
            BRNE    Two
            MOVE    B, A
            ADDI    B, 3
            JUMP    End
Two:        LOADI   C, 2
            CMP     A, C
            BRNE    Default
            MOVE    B, A
            SUBI    B, 1
            JUMP    End
Default:    MOVE    B, A
            SHIFTR  B
End:        STORE   [y], B
            NOOP
```

not mapped to instruction; just goes to next line

Working with Arrays

C vs. Assembly

```c
// Array
//
// C version


int array[]={1, 2, 3, 4};

int main()
{
        array[0]  = 0;

        array[1] += 5;

        array[2] -= 1;

        array[3] += array[2];
}
```

```
; Array
;
; Assembly version

.data
array   BYTE    1, 2, 3, 4

.code
        LOADI   A, 0
        STORE   [array + 0], A
        LOAD    B, [array + 1]
        ADDI    B, 5
        STORE   [array + 1], B
        LOAD    C, [array + 2]
        SUBI    C, 1
        STORE   [array + 2], C
        LOAD    D, [array + 3]
        ADD     D, C
        STORE   [array + 3], D
```

C vs. Assembly

```c
// Array
//
// C version


int array[]={1, 2, 3, 4};

int main()
{
        array[0]  = 0;

        array[1] += 5;

        array[2] -= 1;

        array[3] += array[2];
}
```

```
; Array
;
; Assembly version

.data
array   BYTE    1, 2, 3, 4

.code
        LOADI   A, 0
        STORE   [array + 0], A
        LOAD    B, [array + 1]
        ADDI    B, 5
        STORE   [array + 1], B
        LOAD    C, [array + 2]
        SUBI    C, 1
        STORE   [array + 2], C
        LOAD    D, [array + 3]
        ADD     D, C
        STORE   [array + 3], D
```

C vs. Assembly

```c
// Array
//
// C version


int array[]={1, 2, 3, 4};

int main()
{
        array[0]  = 0;

        array[1] += 5;

        array[2] -= 1;

        array[3] += array[2];
}
```

```
; Array
;
; Assembly version

.data
array   BYTE    1, 2, 3, 4

.code
        LOADI   A, 0
        STORE   [array + 0], A
        LOAD    B, [array + 1]
        ADDI    B, 5
        STORE   [array + 1], B
        LOAD    C, [array + 2]
        SUBI    C, 1
        STORE   [array + 2], C
        LOAD    D, [array + 3]
        ADD     D, C
        STORE   [array + 3], D
```

Machine Code vs. Assembly

```
// Machine Code
ADDR:   DMEM
0000: 00000001
0001: 00000010
0010: 00000011
0011: 00000100

IMEM
0011_00_00_00000000
1010_00_00_00000000
1000_01_00_00000001
0101_01_00_00000101
1010_01_00_00000001
1000_10_00_00000010
0111_10_00_00000001
1010_10_00_00000010
1000_11_00_00000011
0100_11_10_00000000
1010_11_00_00000011
```

```
; Array
;
; Assembly version

.data
array   BYTE    1, 2, 3, 4

.code
        LOADI   A, 0
        STORE   [array + 0], A
        LOAD    B, [array + 1]
        ADDI    B, 5
        STORE   [array + 1], B
        LOAD    C, [array + 2]
        SUBI    C, 1
        STORE   [array + 2], C
        LOAD    D, [array + 3]
        ADD     D, C
        STORE   [array + 3], D
```

Machine Code vs. Assembly

```
// Machine Code
ADDR:   DMEM
0000: 00000001
0001: 00000010
0010: 00000011
0011: 00000100

IMEM
0011_00_00_00000000
1010_00_00_00000000
1000_01_00_00000001
0101_01_00_00000101
1010_01_00_00000001
1000_10_00_00000010
0111_10_00_00000001
1010_10_00_00000010
1000_11_00_00000011
0100_11_10_00000000
1010_11_00_00000011
```

```
; Array
;
; Assembly version

.data
array   BYTE    1, 2, 3, 4

.code
        LOADI   A, 0
        STORE   [array + 0], A
        LOAD    B, [array + 1]
        ADDI    B, 5
        STORE   [array + 1], B
        LOAD    C, [array + 2]
        SUBI    C, 1
        STORE   [array + 2], C
        LOAD    D, [array + 3]
        ADD     D, C
        STORE   [array + 3], D
```

Machine Code vs. Assembly

```
// Machine Code
ADDR:   DMEM
0000: 00000001
0001: 00000010
0010: 00000011
0011: 00000100

IMEM
0011_00_00_00000000
1010_00_00_00000000
1000_01_00_00000001
0101_01_00_00000101
1010_01_00_00000001
1000_10_00_00000010
0111_10_00_00000001
1010_10_00_00000010
1000_11_00_00000011
0100_11_10_00000000
1010_11_00_00000011
```

```
; Array
;
; Assembly version

.data
array   BYTE    1, 2, 3, 4

.code
        LOADI   A, 0
        STORE   [array + 0], A
        LOAD    B, [array + 1]
        ADDI    B, 5
        STORE   [array + 1], B
        LOAD    C, [array + 2]
        SUBI    C, 1
        STORE   [array + 2], C
        LOAD    D, [array + 3]
        ADD     D, C
        STORE   [array + 3], D
```

Working with Arrays
And Looping Over Their Elements

C vs. Assembly

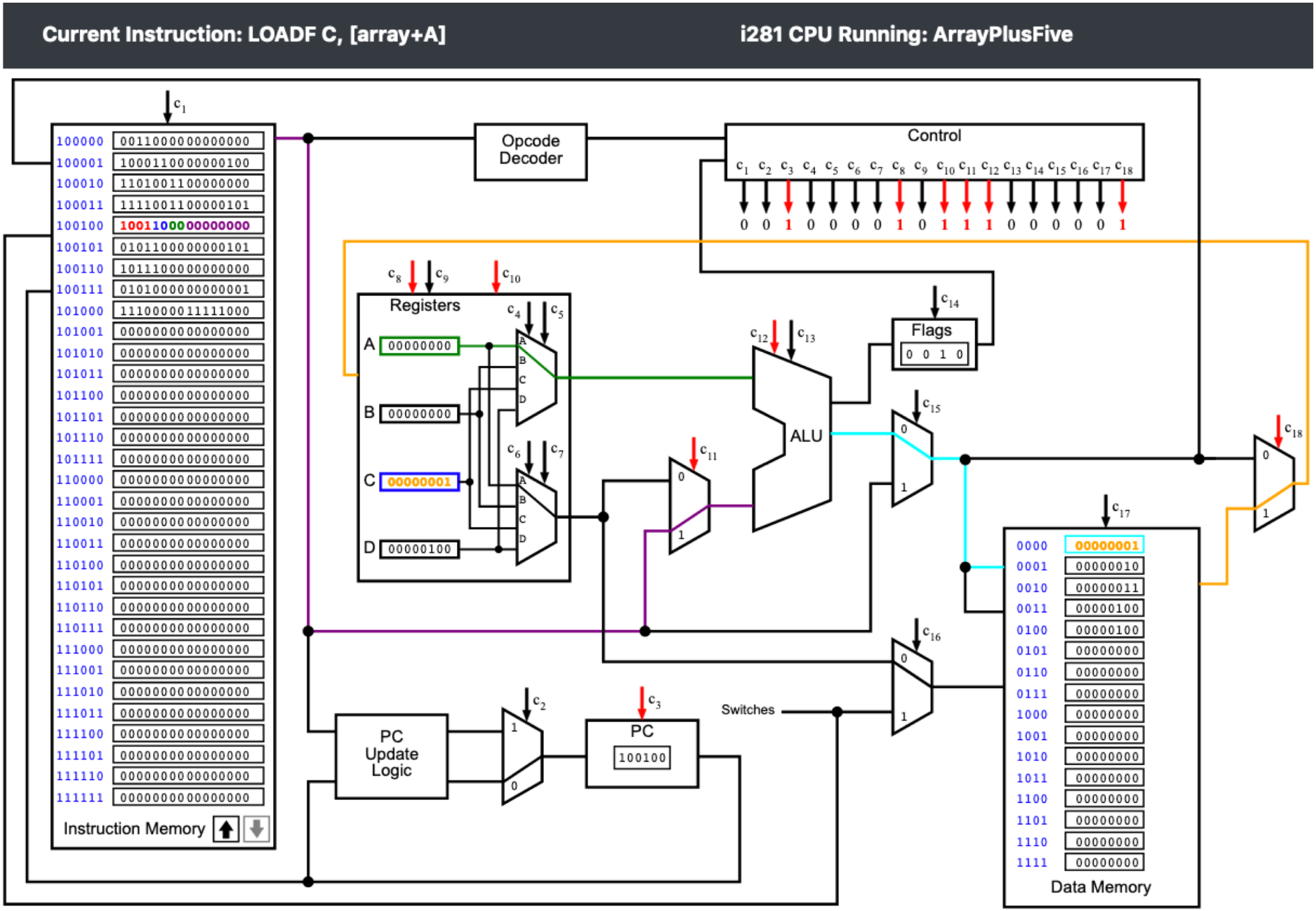
```c
// Array plus 5
// C version


int array[]={1, 2, 3, 4};
int N = 4;



int main()
{
    int i;

    // add 5 to all elements
    for( i=0; i< N; i++)
    {
        array[i] += 5;
    }
}
```

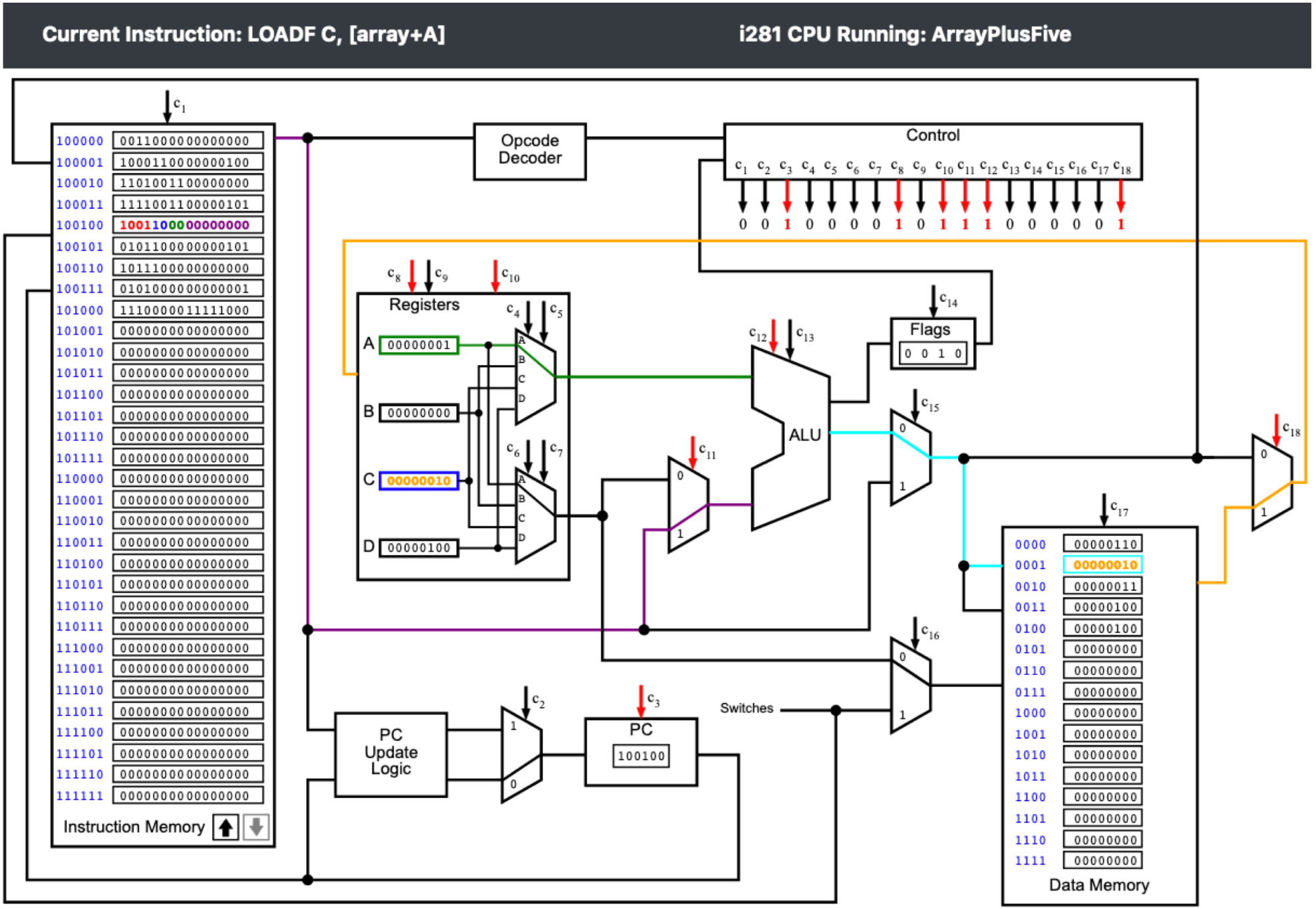
```
; Array plus 5
; Assembly version

.data
array   BYTE    1, 2, 3, 4
N       BYTE    4
.code
        LOADI   A, 0              ; i = 0
For:    LOAD    D, [N]            ; D <- N
        CMP     A, D              ; i < N ?
        BRGE    End               ; if no, exit loop
        LOADF   C, [array + A]    ; load array[i]
        ADDI    C, 5              ; add 5
        STOREF  [array + A], C    ; store the result
Iinc:   ADDI    A, 1              ; i++
        JUMP    For               ; next iteration
End:    NOOP

; Register allocation:
; A: i
; B: <not used>
; C: temp variable for loading the array elements
; D: N
```

C vs. Assembly

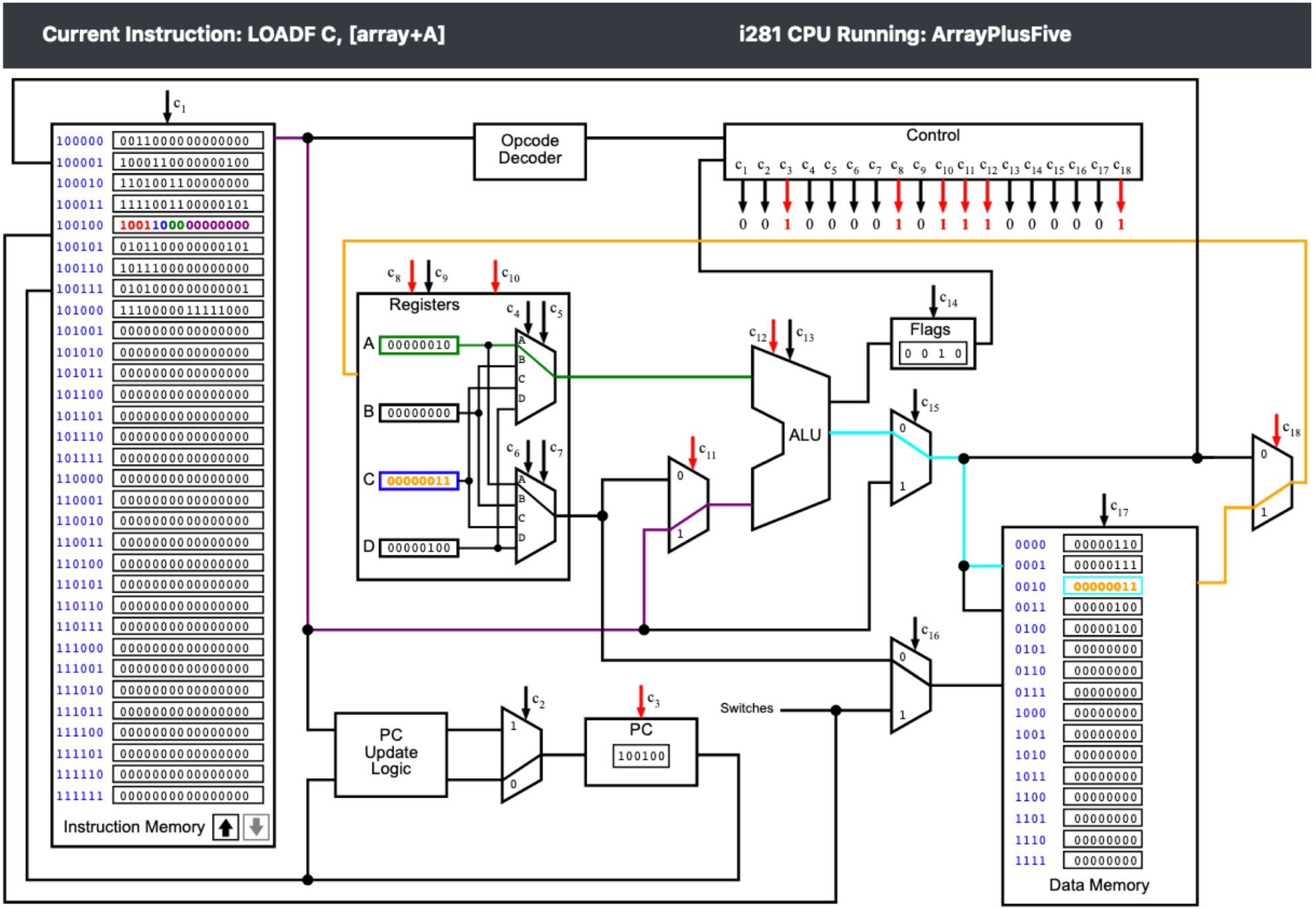
```c
// Array plus 5
// C version


int array[]={1, 2, 3, 4};
int N = 4;


int main()
{
    int i;

    // add 5 to all elements
    for( i=0; i< N; i++)
    {
        array[i] += 5;
    }
}
```

```
; Array plus 5
; Assembly version

.data
array   BYTE    1, 2, 3, 4
N       BYTE    4
.code
        LOADI   A, 0                ; i = 0
For:    LOAD    D, [N]              ; D <- N
        CMP     A, D                ; i < N ?
        BRGE    End                 ; if no, exit loop
        LOADF   C, [array + A]      ; load array[i]
        ADDI    C, 5                ; add 5
        STOREF  [array + A], C      ; store the result
Iinc:   ADDI    A, 1                ; i++
        JUMP    For                 ; next iteration
End:    NOOP

; Register allocation:
; A: i
; B: <not used>
; C: temp variable for loading the array elements
; D: N
```

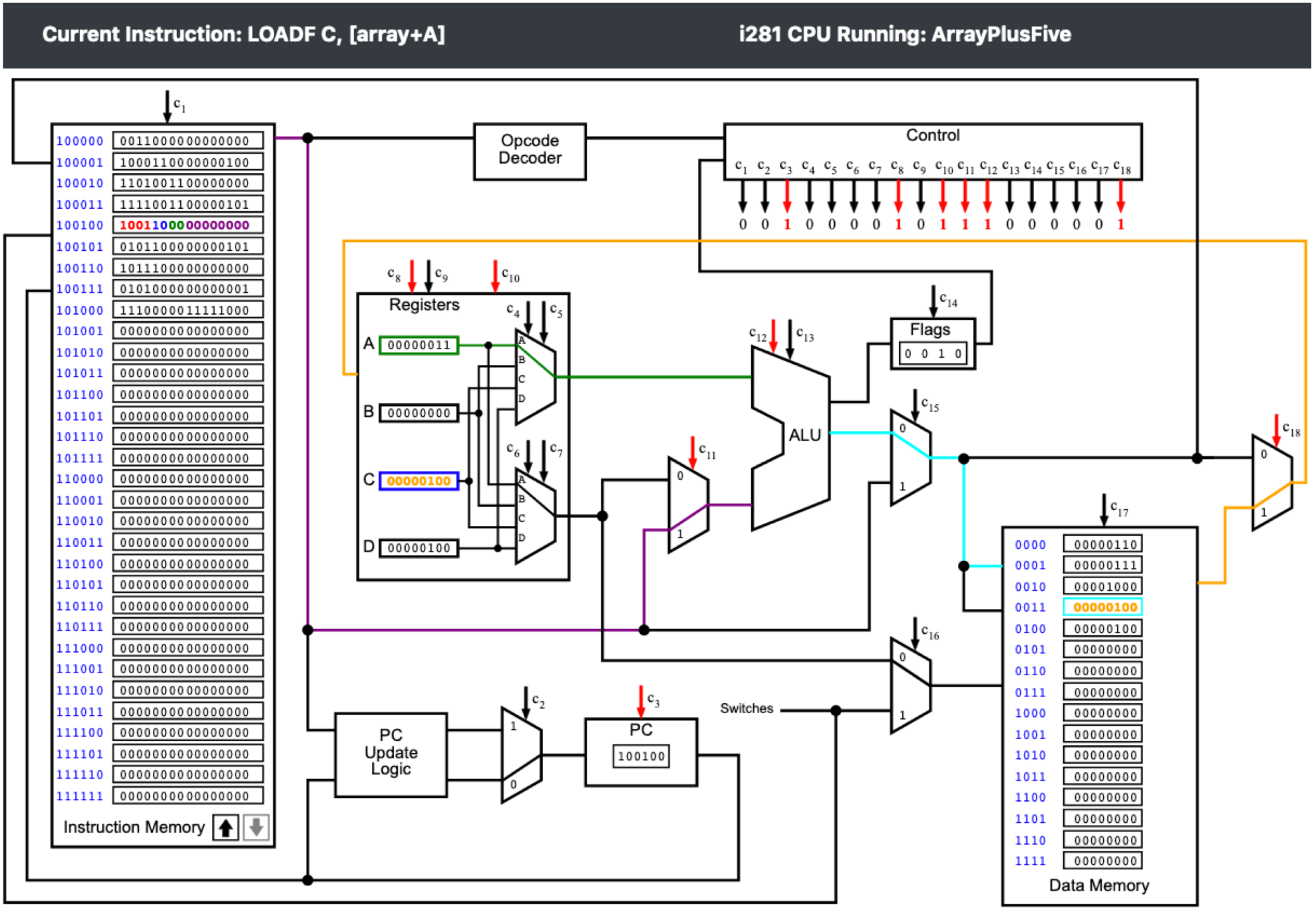

Current Instruction: LOADF C, [array+A]
i281 CPU Running: ArrayPlusFive
Opcode Decoder
Control
Registers
A 00000000
B 00000000
C 00000001
D 00000100
Flags
0 0 1 0
ALU
PC
100100
PC Update Logic
Switches
Instruction Memory
Data Memory



2nd iteration



3rd iteration



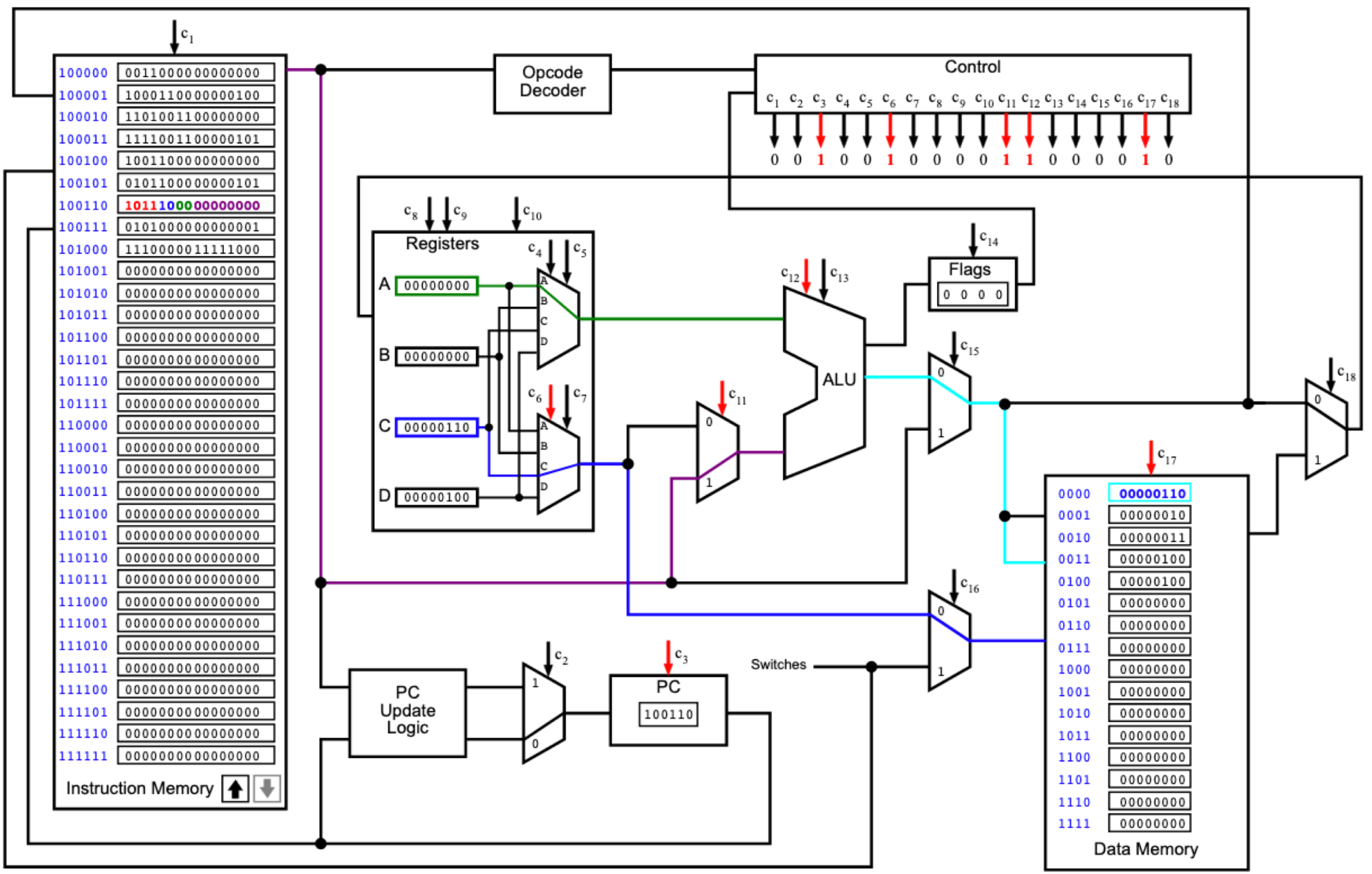
4th iteration

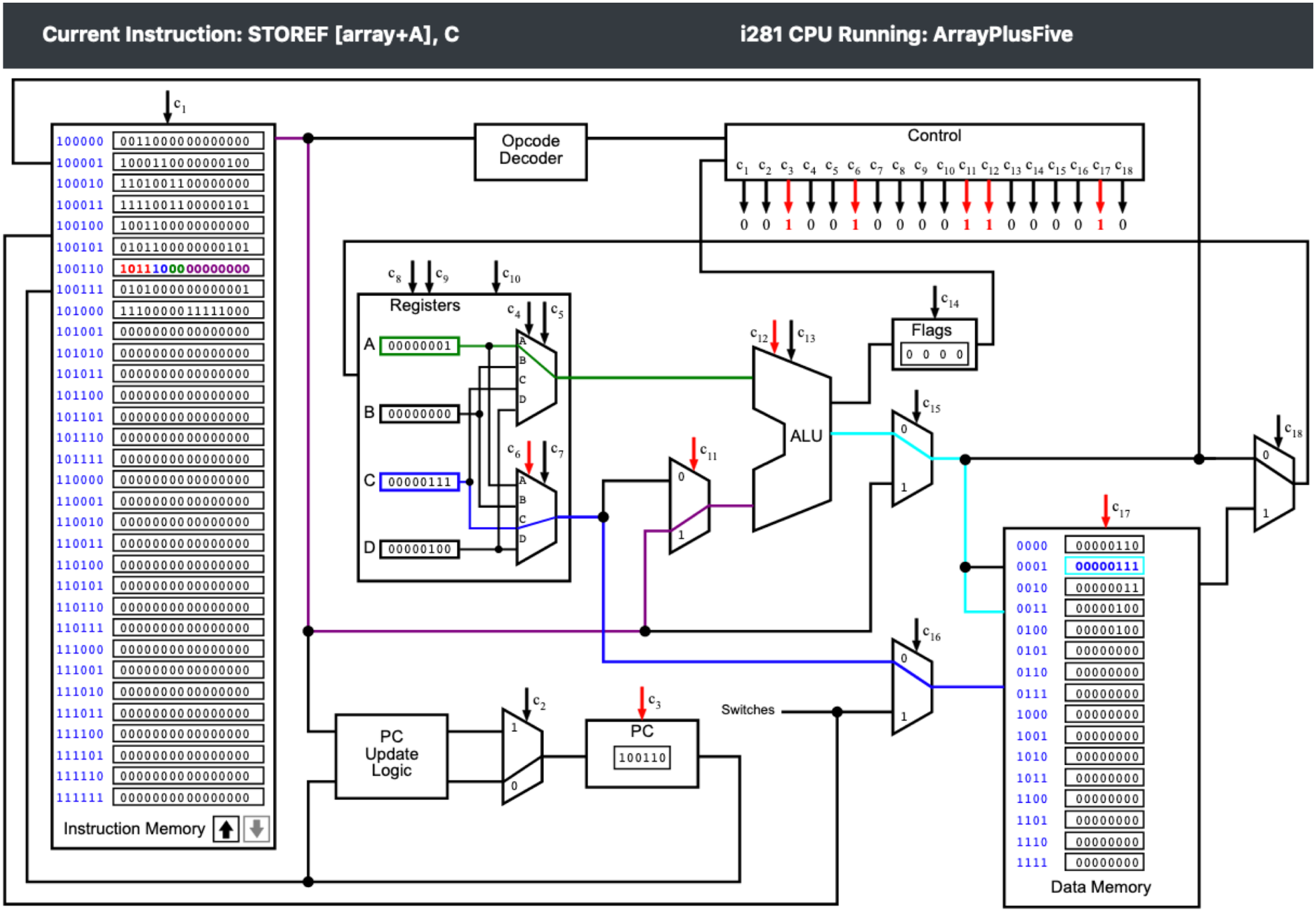
C vs. Assembly

```c
// Array plus 5
// C version


int array[]={1, 2, 3, 4};
int N = 4;


int main()
{
    int i;

    // add 5 to all elements
    for( i=0; i< N; i++)
    {
        array[i] += 5;
    }
}
```

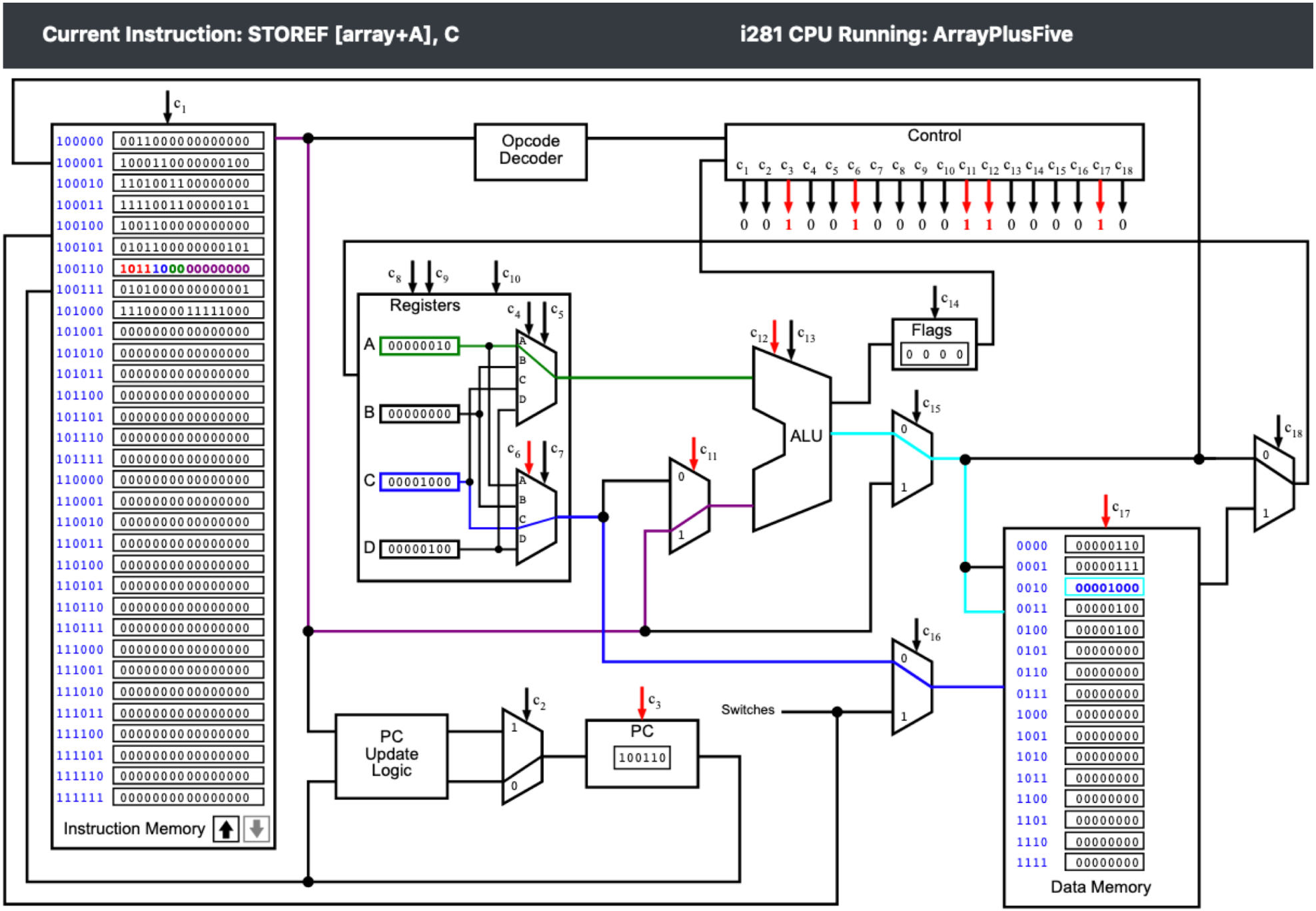
```
; Array plus 5
; Assembly version

.data
array   BYTE    1, 2, 3, 4
N       BYTE    4
.code
        LOADI   A, 0                ; i = 0
For:    LOAD    D, [N]              ; D <- N
        CMP     A, D                ; i < N ?
        BRGE    End                 ; if no, exit loop
        LOADF   C, [array + A]      ; load array[i]
        ADDI    C, 5                ; add 5
        STOREF  [array + A], C      ; store the result
Iinc:   ADDI    A, 1                ; i++
        JUMP    For                 ; next iteration
End:    NOOP

; Register allocation:
; A: i
; B: <not used>
; C: temp variable for loading the array elements
; D: N
```

Current Instruction: STOREF [array+A], C **i281 CPU Running: ArrayPlusFive**



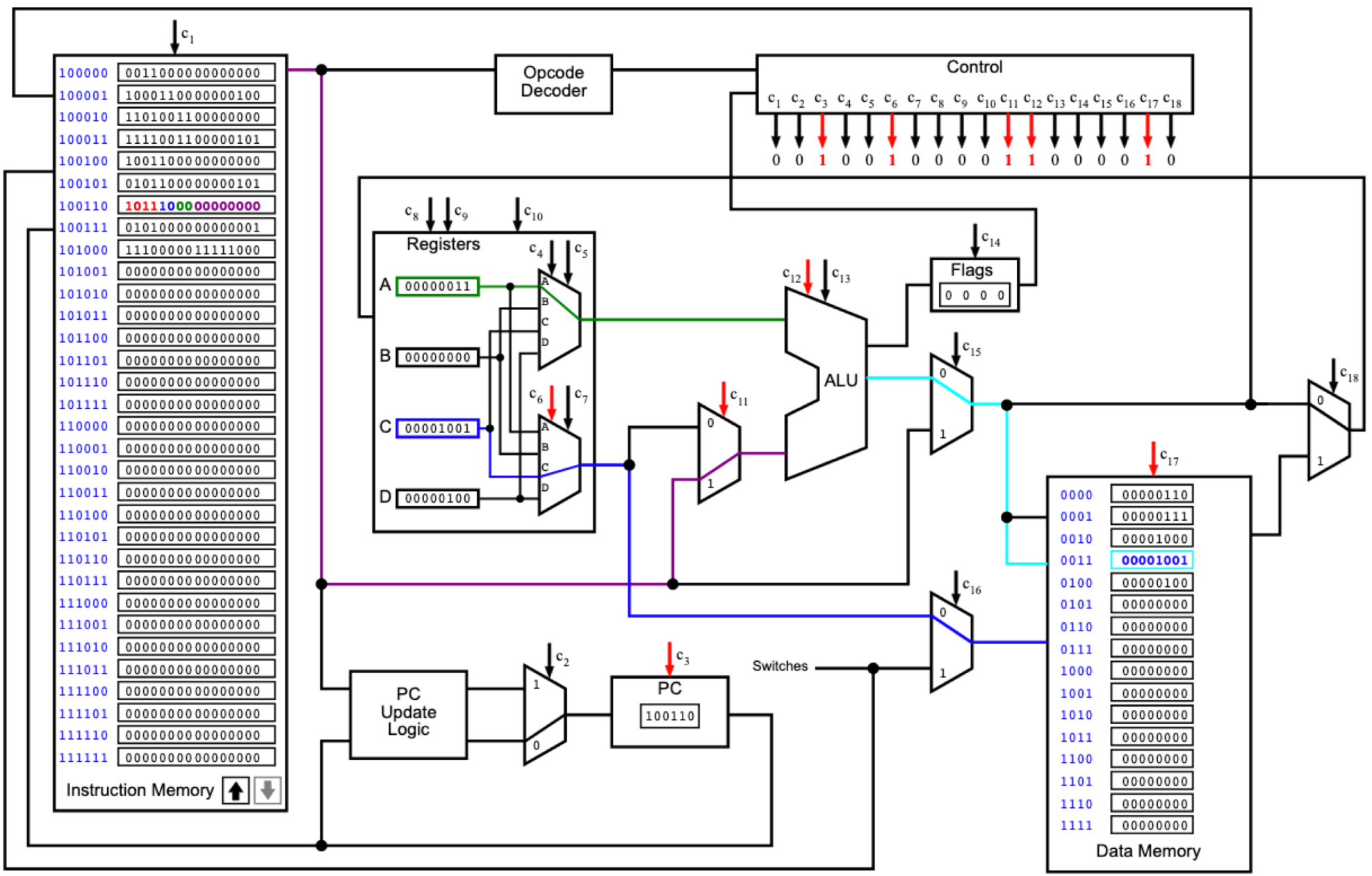


2nd iteration



3rd iteration

Current Instruction: STOREF [array+A], C **i281 CPU Running: ArrayPlusFive**



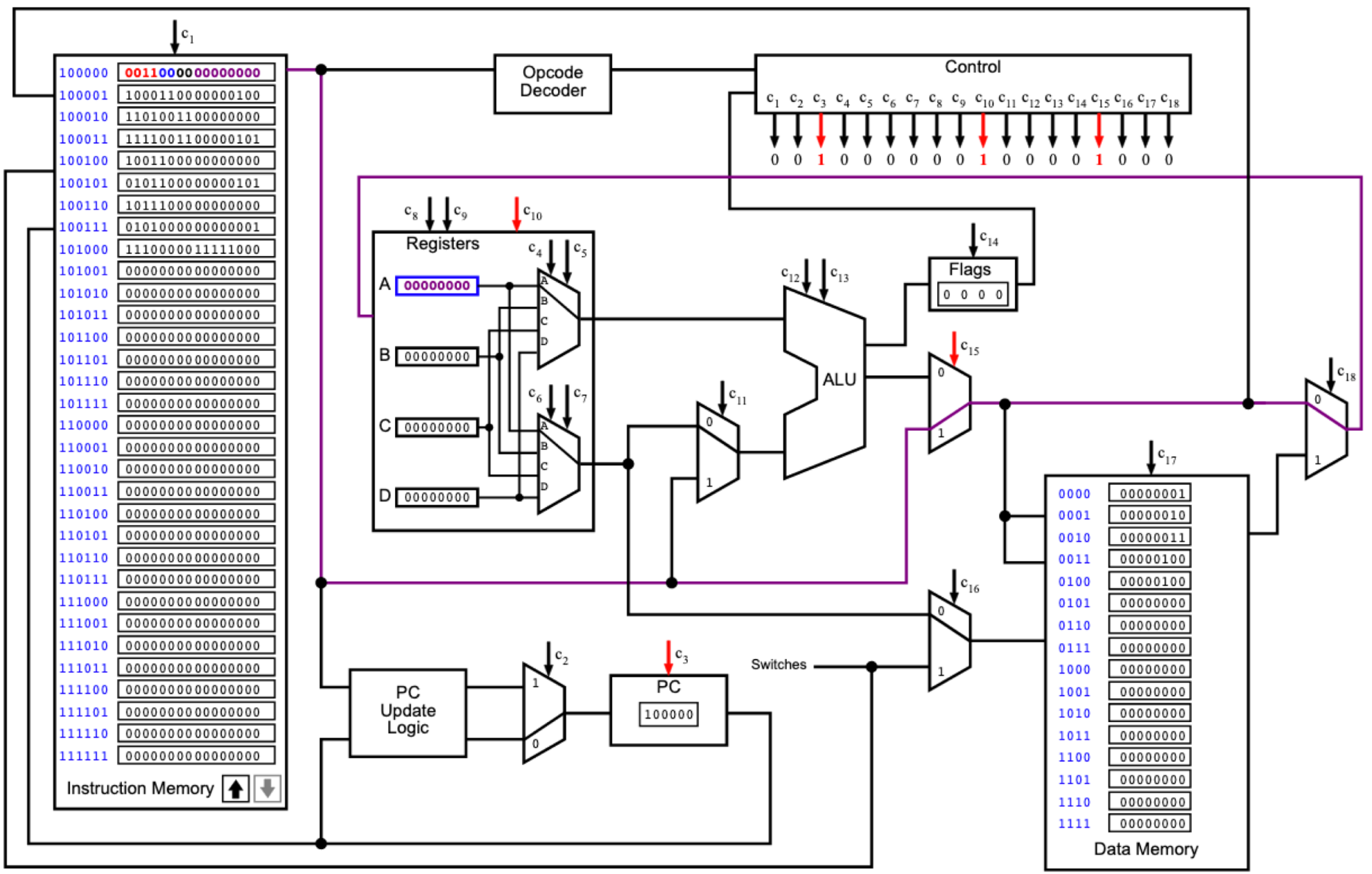
4th iteration

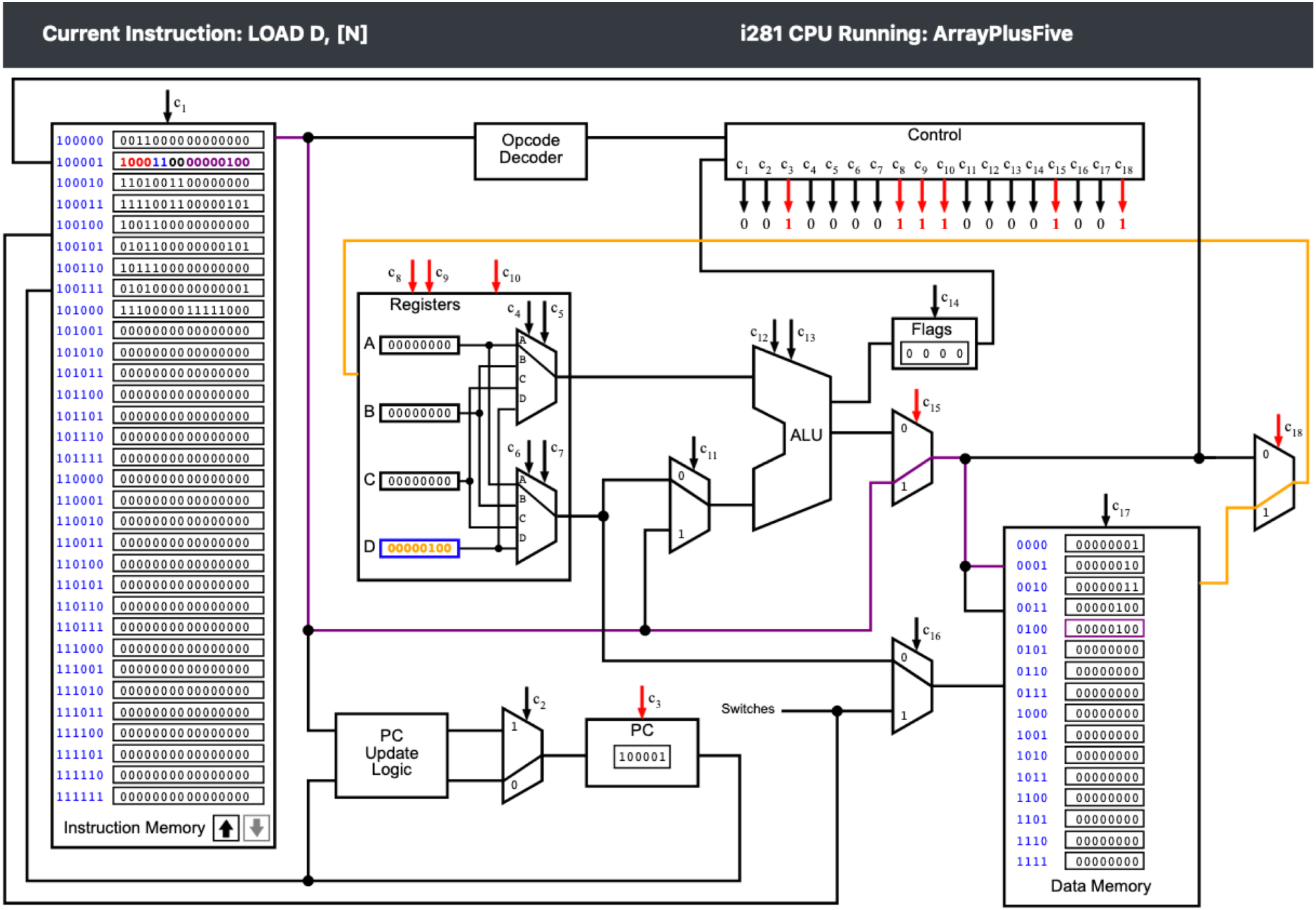
C vs. Assembly

```c
// Array plus 5
// C version


int array[]={1, 2, 3, 4};
int N = 4;



int main()
{
    int i;

    // add 5 to all elements
    for( i=0; i< N; i++)
    {
        array[i] += 5;
    }
}
```

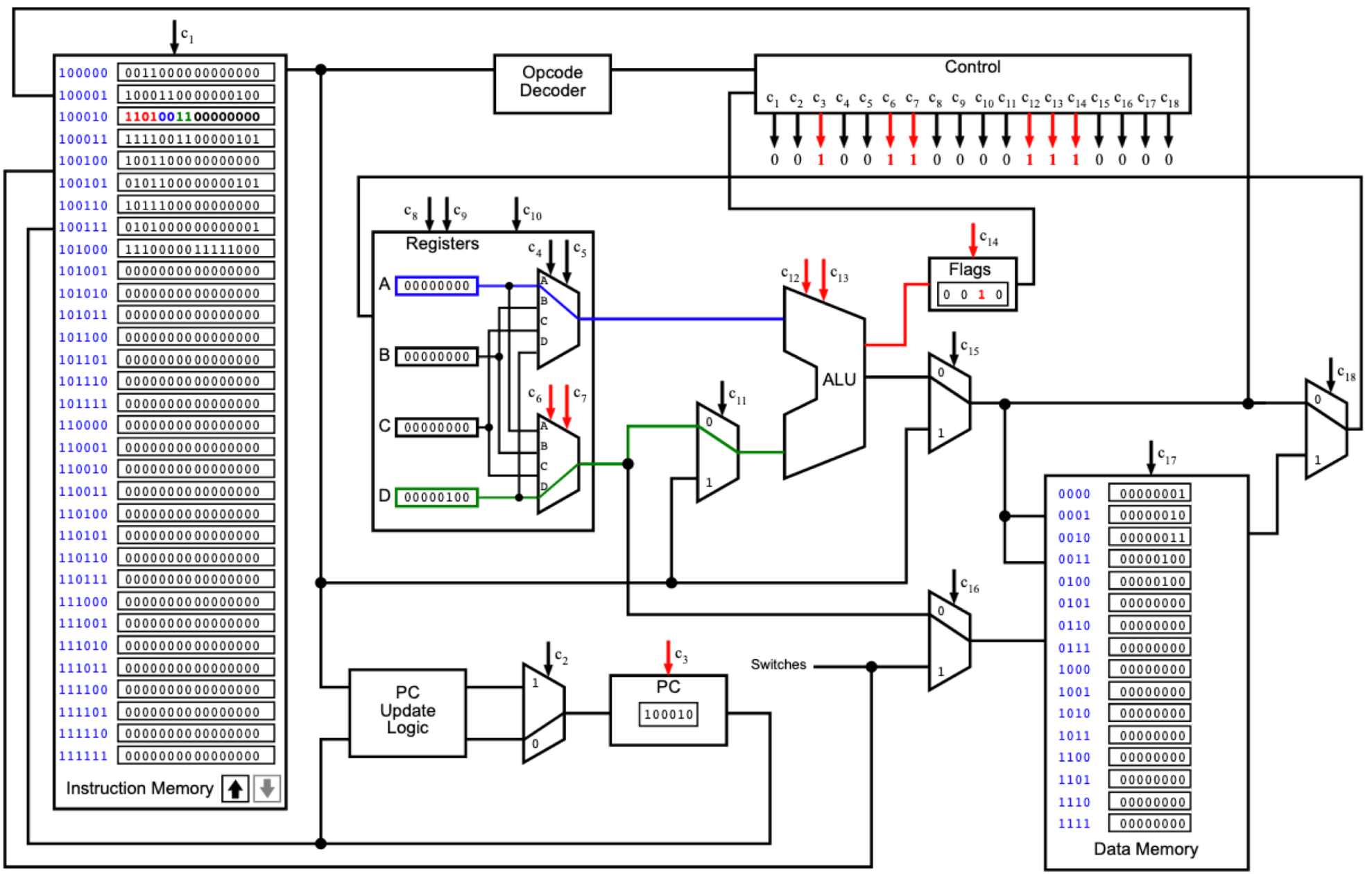
```
; Array plus 5
; Assembly version

.data
array   BYTE    1, 2, 3, 4
N       BYTE    4
.code
        LOADI   A, 0              ; i = 0
For:    LOAD    D, [N]            ; D <- N
        CMP     A, D              ; i < N ?
        BRGE    End               ; if no, exit loop
        LOADF   C, [array + A]    ; load array[i]
        ADDI    C, 5              ; add 5
        STOREF  [array + A], C    ; store the result
Iinc:   ADDI    A, 1              ; i++
        JUMP    For               ; next iteration
End:    NOOP

; Register allocation:
; A: i
; B: <not used>
; C: temp variable for loading the array elements
; D: N
```

Current Instruction: LOADI A, 0 **i281 CPU Running: ArrayPlusFive**

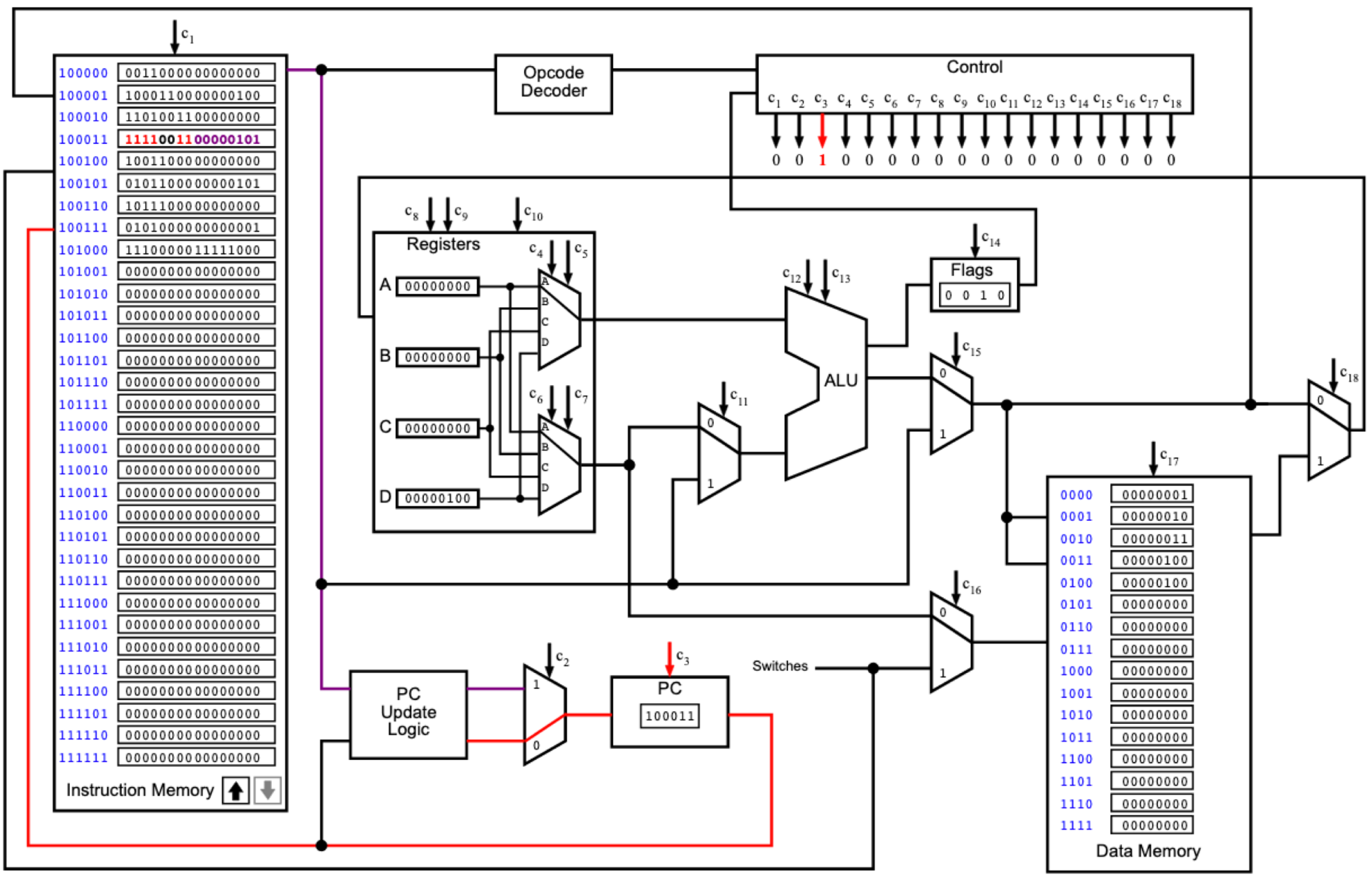


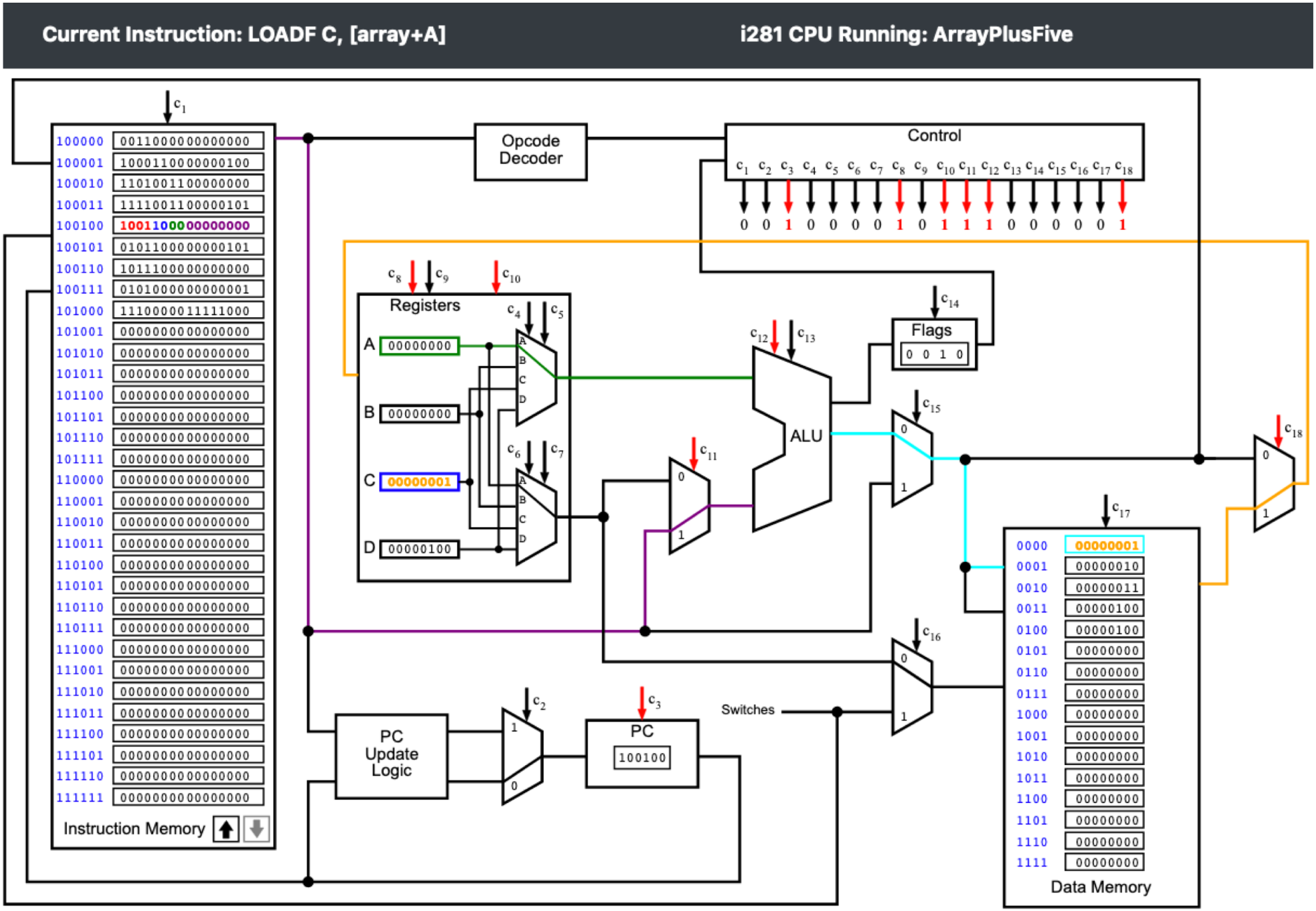

Current Instruction: LOAD D, [N]
i281 CPU Running: ArrayPlusFive
c1
100000 0011000000000000
100001 1000110000000100
100010 1101001100000000
100011 1111001100000101
100100 1001100000000000
100101 0101100000000101
100110 1011100000000000
100111 0101000000000001
101000 1110000011111000
101001 0000000000000000
101010 0000000000000000
101011 0000000000000000
101100 0000000000000000
101101 0000000000000000
101110 0000000000000000
101111 0000000000000000
110000 0000000000000000
110001 0000000000000000
110010 0000000000000000
110011 0000000000000000
110100 0000000000000000
110101 0000000000000000
110110 0000000000000000
110111 0000000000000000
111000 0000000000000000
111001 0000000000000000
111010 0000000000000000
111011 0000000000000000
111100 0000000000000000
111101 0000000000000000
111110 0000000000000000
111111 0000000000000000
Instruction Memory
Opcode Decoder
Control
c1 c2 c3 c4 c5 c6 c7 c8 c9 c10 c11 c12 c13 c14 c15 c16 c17 c18
0 0 1 0 0 0 0 1 1 1 0 0 0 0 1 0 0 1
c8 c9 c10
Registers
c4 c5
A 00000000
B 00000000
C 00000000
D 00000100
c6 c7
c11
c12 c13
ALU
c14
Flags
0 0 0 0
c15
c18
c17
0000 00000001
0001 00000010
0010 00000011
0011 00000100
0100 00000100
0101 00000000
0110 00000000
0111 00000000
1000 00000000
1001 00000000
1010 00000000
1011 00000000
1100 00000000
1101 00000000
1110 00000000
1111 00000000
Data Memory
c16
Switches
PC Update Logic
c2
c3
PC
100001

Current Instruction: CMP A, D **i281 CPU Running: ArrayPlusFive**

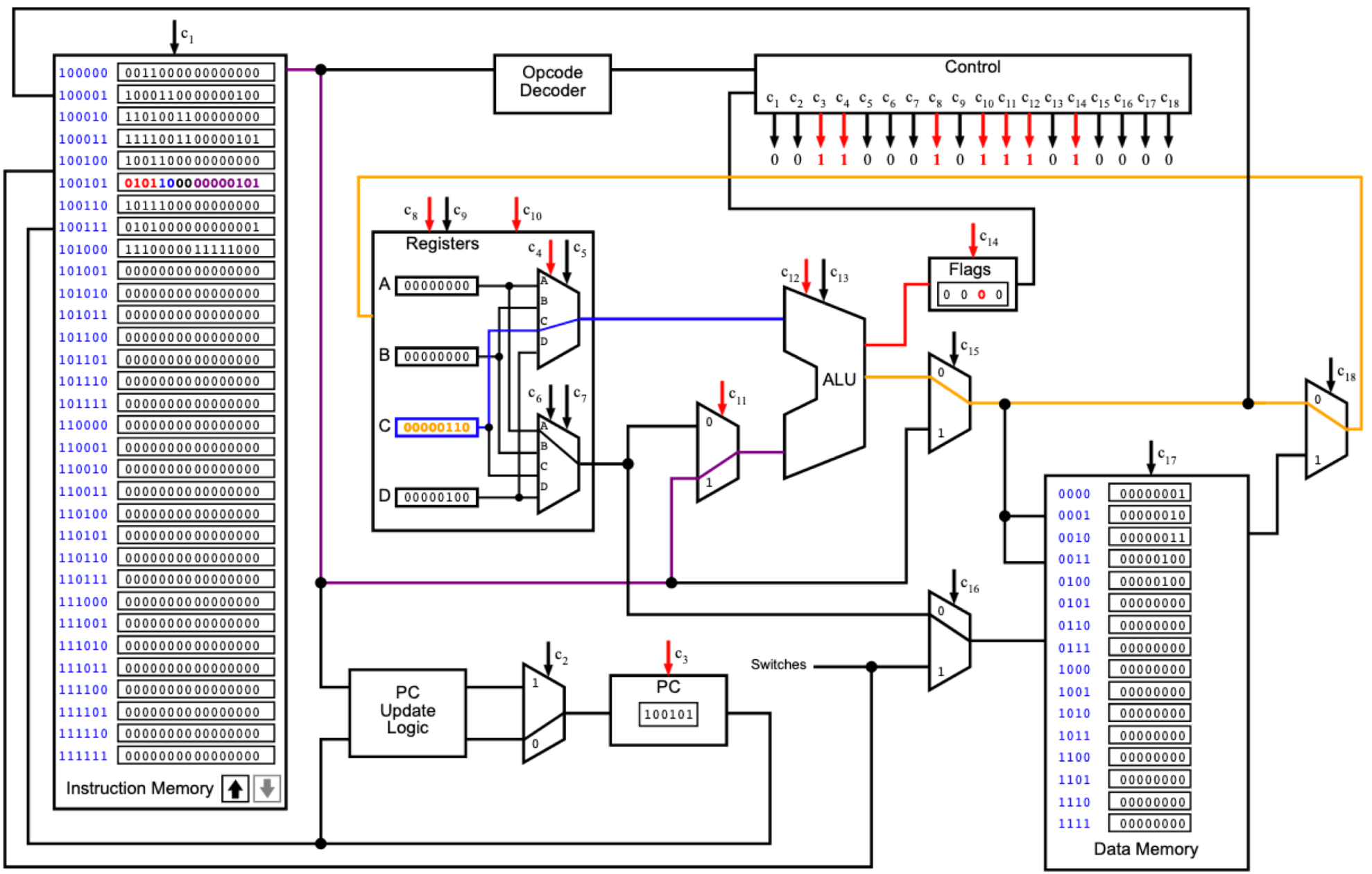


Current Instruction: BRGE End **i281 CPU Running: ArrayPlusFive**

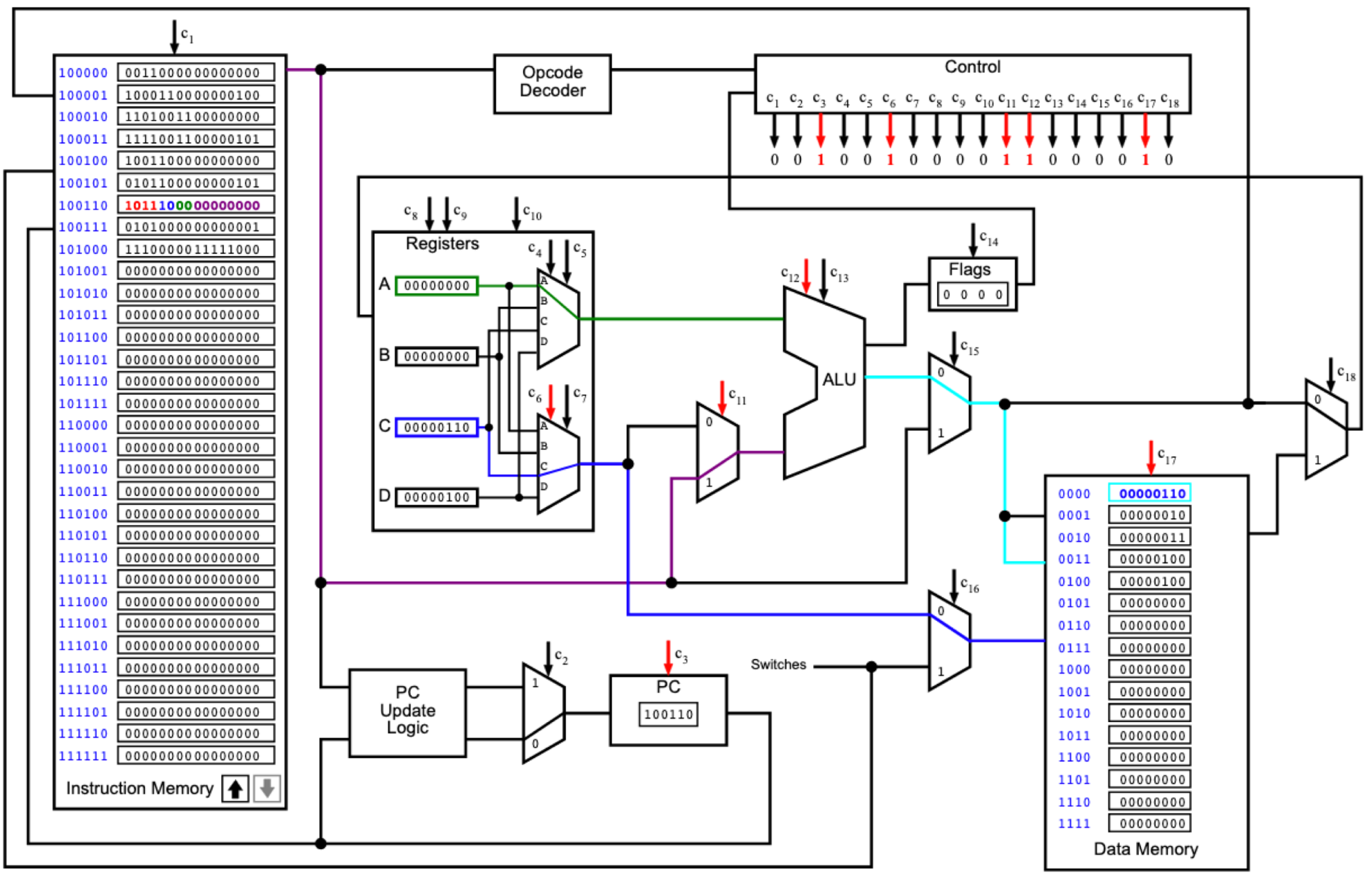


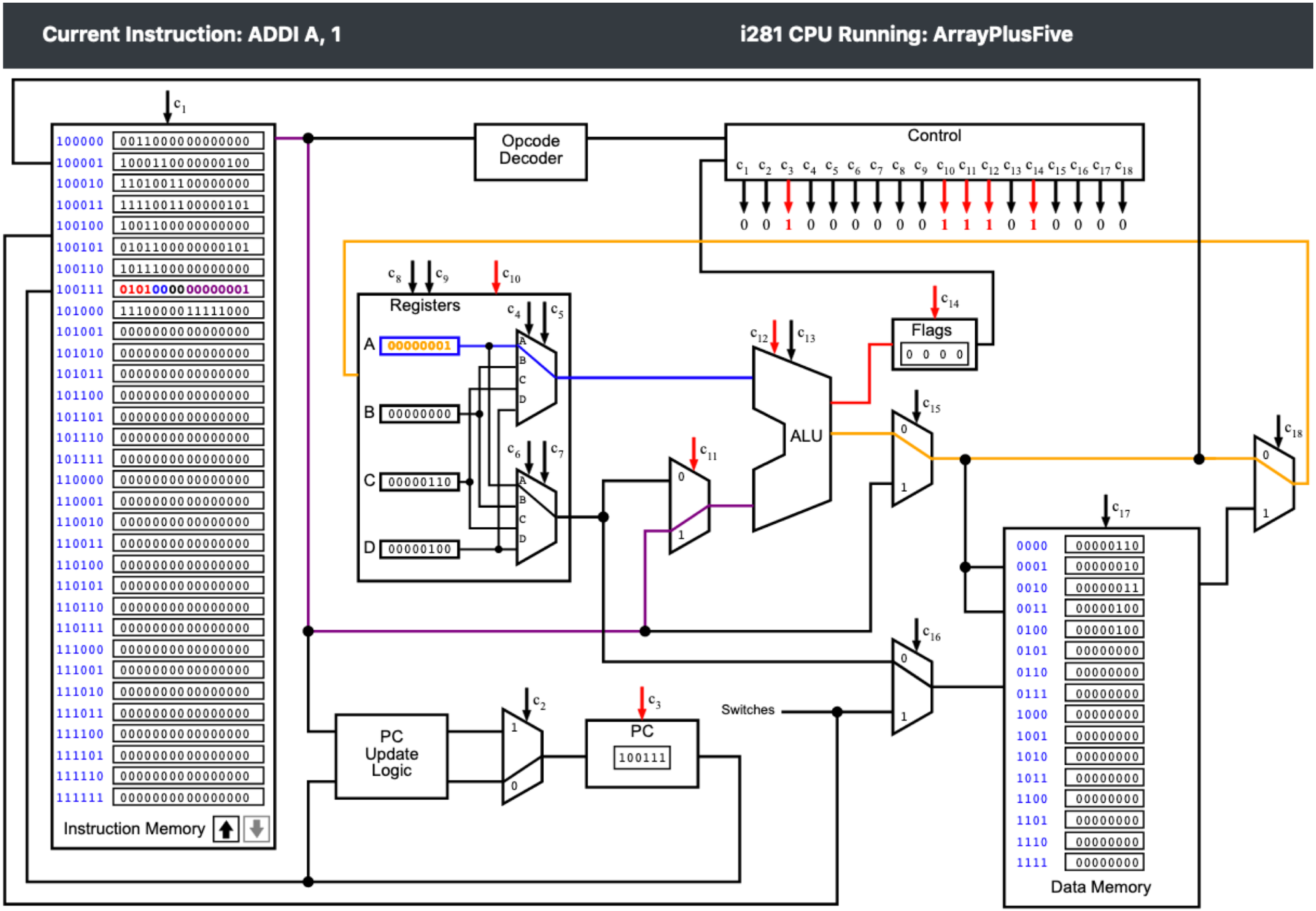

Current Instruction: LOADF C, [array+A]
i281 CPU Running: ArrayPlusFive
Opcode Decoder
Control
Registers
A 00000000
B 00000000
C 00000001
D 00000100
Flags
0 0 1 0
ALU
PC
100100
PC Update Logic
Switches
Instruction Memory
Data Memory

Current Instruction: ADDI C, 5 **i281 CPU Running: ArrayPlusFive**

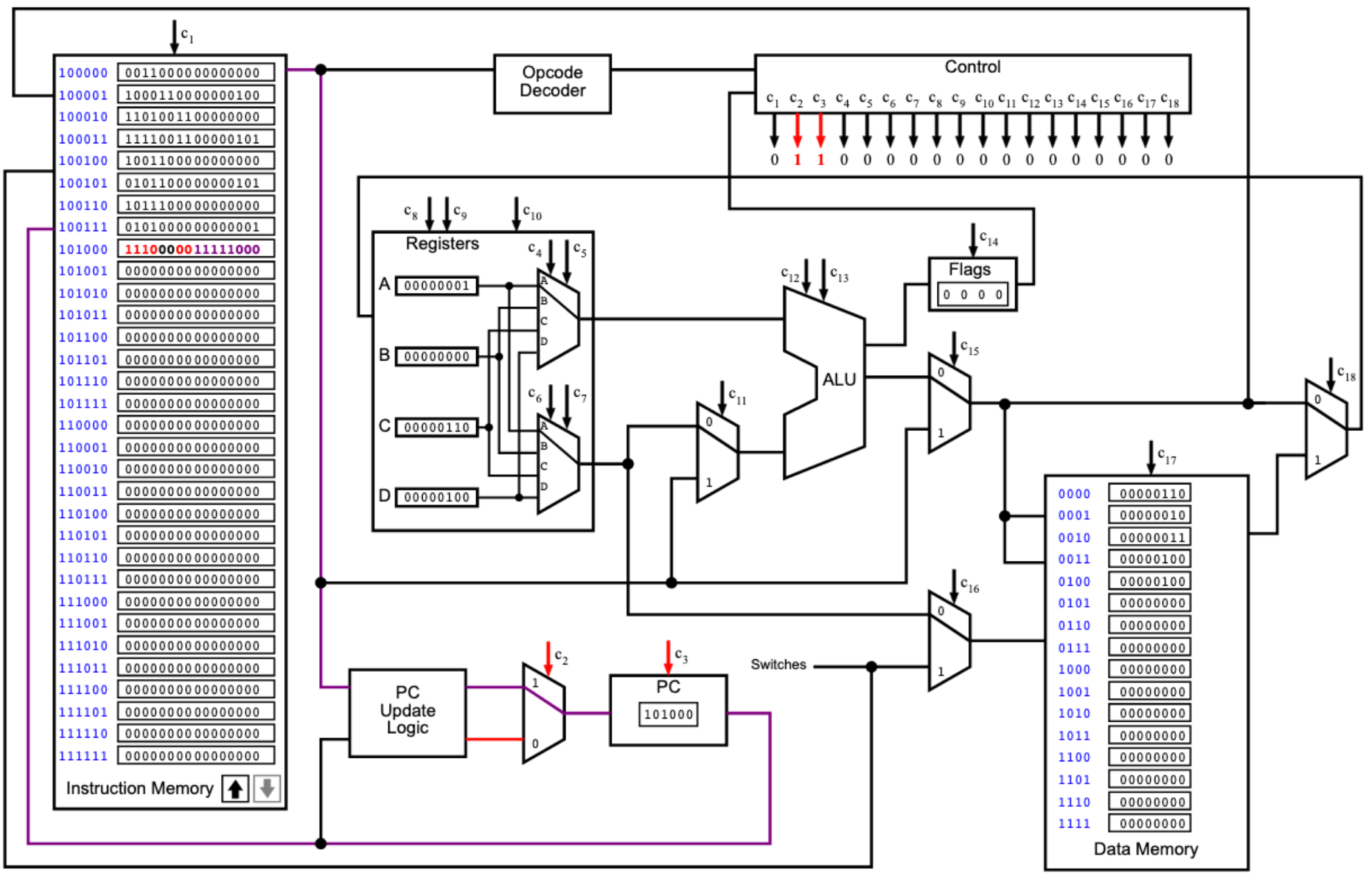


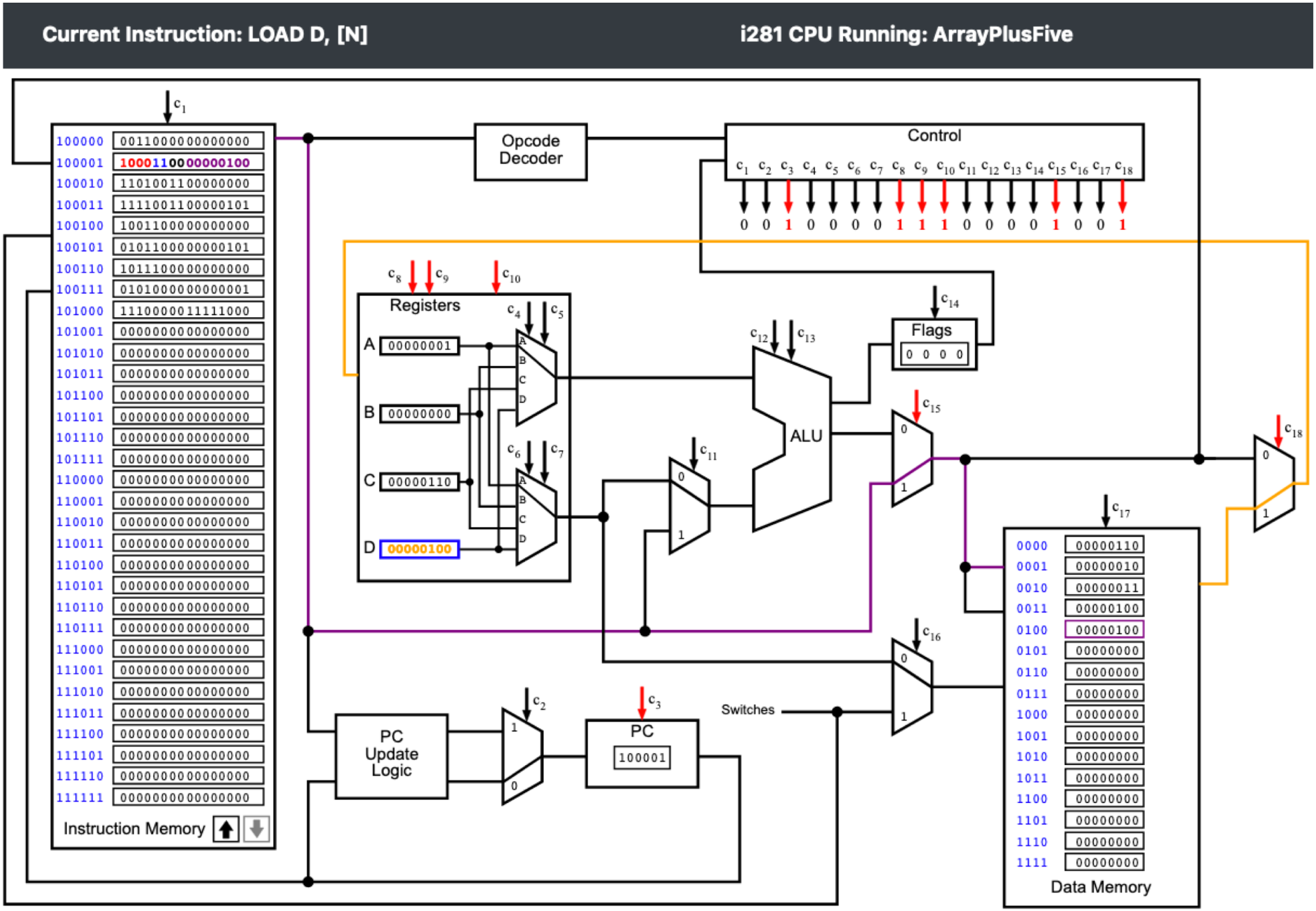
Current Instruction: STOREF [array+A], C **i281 CPU Running: ArrayPlusFive**




Current Instruction: ADDI A, 1
i281 CPU Running: ArrayPlusFive
Opcode Decoder
Control
Registers
Flags
ALU
PC
Update Logic
Switches
Instruction Memory
Data Memory

Current Instruction: JUMP For **i281 CPU Running: ArrayPlusFive**




Current Instruction: LOAD D, [N]
i281 CPU Running: ArrayPlusFive
c1
100000 0011000000000000
100001 1000110000000100
100010 1101001100000000
100011 1111001100000101
100100 1001100000000000
100101 0101100000000101
100110 1011100000000000
100111 0101000000000001
101000 1110000011111000
101001 0000000000000000
101010 0000000000000000
101011 0000000000000000
101100 0000000000000000
101101 0000000000000000
101110 0000000000000000
101111 0000000000000000
110000 0000000000000000
110001 0000000000000000
110010 0000000000000000
110011 0000000000000000
110100 0000000000000000
110101 0000000000000000
110110 0000000000000000
110111 0000000000000000
111000 0000000000000000
111001 0000000000000000
111010 0000000000000000
111011 0000000000000000
111100 0000000000000000
111101 0000000000000000
111110 0000000000000000
111111 0000000000000000
Instruction Memory
Opcode Decoder
Control
c1 c2 c3 c4 c5 c6 c7 c8 c9 c10 c11 c12 c13 c14 c15 c16 c17 c18
0 0 1 0 0 0 0 1 1 1 0 0 0 0 1 0 0 1
c8 c9 c10
Registers
c4 c5
A 00000001
B 00000000
C 00000110
D 00000100
c6 c7
c11
c12 c13
ALU
c14
Flags
0 0 0 0
c15
c18
c17
0000 00000110
0001 00000010
0010 00000011
0011 00000100
0100 00000100
0101 00000000
0110 00000000
0111 00000000
1000 00000000
1001 00000000
1010 00000000
1011 00000000
1100 00000000
1101 00000000
1110 00000000
1111 00000000
Data Memory
c16
Switches
c2
c3
PC Update Logic
PC
100001

For Loop Example:
Add the numbers from 1 to 5

For Loop Example:
Add the numbers from 1 to 5

C Language v.s. Assembly Language

C Version

```
// C Version
//
// Add the numbers from 1 to 5 using a for loop.

int main()
{
        int N=5;
        int i, sum;

        sum=0;
        for(i=1; i<=N; i++)
           sum+=i;

        // printf("%d\n", sum);
}
```

i281 Assembly Version

```
.data
N         BYTE    5
i         BYTE    ?
sum       BYTE    ?

.code
          LOADI   B, 0          ; sum=0
          LOADI   A, 1          ; i=1
          LOAD    D, [N]        ; register_D=N
Loop:     CMP     A, D          ; i<=N ?
          BRG     End           ; exit if i>N
Add:      ADD     B, A          ; sum+=i
          ADDI    A, 1          ; i++
          JUMP    Loop          ; next iteration
End:      STORE   [sum], B      ; update the memory for sum

; Register allocation:
; A: i
; B: sum
; C: <not used>
; D: N
```

i281 Assembly Version

```
.data
N         BYTE    5
i         BYTE    ?
sum       BYTE    ?

.code
          LOADI   B, 0          ; sum=0
          LOADI   A, 1          ; i=1
          LOAD    D, [N]        ; register_D=N
Loop:     CMP     A, D          ; i<=N ?
          BRG     End           ; exit if i>N
Add:      ADD     B, A          ; sum+=i
          ADDI    A, 1          ; i++
          JUMP    Loop          ; next iteration
End:      STORE   [sum], B      ; update the memory for sum

; Register allocation:
; A: i
; B: sum
; C: <not used>
; D: N
```

Add the numbers from 1 to 5

```c
// C Version
// using a for loop



int main()
{
        int N=5;
        int i, sum;

        sum=0;
        for(i=1; i<=N; i++) {
           sum+=i;
        }

        // printf("%d\n", sum);
}
```

```
; Assembly Version

.data
N         BYTE    5
i         BYTE    ?
sum       BYTE    ?

.code
          LOADI   B, 0        ; sum=0
          LOADI   A, 1        ; i=1
          LOAD    D, [N]      ; register_D=N
Loop:     CMP     A, D        ; i<=N ?
          BRG     End         ; exit if i>N
Add:      ADD     B, A        ; sum+=i
          ADDI    A, 1        ; i++
          JUMP    Loop        ; next iteration
End:      STORE   [sum], B    ; write B to sum
```

Add the numbers from 1 to 5

```c
// C Version
// using a for loop




int main()
{
        int N=5;
        int i, sum;

        sum=0;
        for(i=1; i<=N; i++) {
           sum+=i;
        }

        // printf("%d\n", sum);
}
```

```
; Assembly Version

.data
N         BYTE    5
i         BYTE    ?
sum       BYTE    ?

.code
          LOADI   B, 0        ; sum=0
          LOADI   A, 1        ; i=1
          LOAD    D, [N]      ; register_D=N
Loop:     CMP     A, D        ; i<=N ?
          BRG     End         ; exit if i>N
Add:      ADD     B, A        ; sum+=i
          ADDI    A, 1        ; i++
          JUMP    Loop        ; next iteration
End:      STORE   [sum], B    ; write B to sum
```

Add the numbers from 1 to 5

```c
// C Version
// using a for loop




int main()
{
        int N=5;
        int i, sum;

        sum=0;
        for(i=1; i<=N; i++) {
           sum+=i;
        }

        // printf("%d\n", sum);
}
```

```
; Assembly Version

.data
N         BYTE    5
i         BYTE    ?
sum       BYTE    ?

.code
          LOADI   B, 0        ; sum=0
          LOADI   A, 1        ; i=1
          LOAD    D, [N]      ; register_D=N
Loop:     CMP     A, D        ; i<=N ?
          BRG     End         ; exit if i>N
Add:      ADD     B, A        ; sum+=i
          ADDI    A, 1        ; i++
          JUMP    Loop        ; next iteration
End:      STORE   [sum], B    ; write B to sum
```

Add the numbers from 1 to 5

```c
// C Version
// using a for loop



int main()
{
        int N=5;
        int i, sum;

        sum=0;
        for(i=1; i<=N; i++) {
           sum+=i;
        }

        // printf("%d\n", sum);
}
```

```
; Assembly Version

.data
N         BYTE    5
i         BYTE    ?
sum       BYTE    ?

.code
          LOADI   B, 0        ; sum=0
          LOADI   A, 1        ; i=1
          LOAD    D, [N]      ; register_D=N
Loop:     CMP     A, D        ; i<=N ?
          BRG     End         ; exit if i>N
Add:      ADD     B, A        ; sum+=i
          ADDI    A, 1        ; i++
          JUMP    Loop        ; next iteration
End:      STORE   [sum], B    ; write B to sum
```

Add the numbers from 1 to 5

```c
// C Version
// using a for loop



int main()
{
        int N=5;
        int i, sum;

        sum=0;
        for(i=1; i<=N; i++) {
           sum+=i;
        }

        // printf("%d\n", sum);
}
```

```
; Assembly Version

.data
N         BYTE    5
i         BYTE    ?
sum       BYTE    ?

.code
          LOADI   B, 0        ; sum=0
          LOADI   A, 1        ; i=1
          LOAD    D, [N]      ; register_D=N
Loop:     CMP     A, D        ; i<=N ?
          BRG     End         ; exit if i>N
Add:      ADD     B, A        ; sum+=i
          ADDI    A, 1        ; i++
          JUMP    Loop        ; next iteration
End:      STORE   [sum], B    ; write B to sum
```

Add the numbers from 1 to 5

```
// C Version
// using a for loop




int main()
{
        int N=5;
        int i, sum;

        sum=0;
        for(i=1; i<=N; i++) {
           sum+=i;
        }

        // printf("%d\n", sum);
}
```

i=1

```
; Assembly Version

.data
N         BYTE    5
i         BYTE    ?
sum       BYTE    ?

.code
          LOADI   B, 0        ; sum=0
          LOADI   A, 1        ; i=1
          LOAD    D, [N]      ; register_D=N
Loop:     CMP     A, D        ; i<=N ?
          BRG     End         ; exit if i>N
Add:      ADD     B, A        ; sum+=i
          ADDI    A, 1        ; i++
          JUMP    Loop        ; next iteration
End:      STORE   [sum], B    ; write B to sum
```

Add the numbers from 1 to 5

```c
// C Version
// using a for loop




int main()
{
        int N=5;
        int i, sum;

        sum=0;
        for(i=1; i<=N; i++) {
           sum+=i;
        }

        // printf("%d\n", sum);
}
```

This has no analog in the C version, which is written in a high-level language.

```
; Assembly Version

.data
N         BYTE    5
i         BYTE    ?
sum       BYTE    ?

.code
          LOADI   B, 0        ; sum=0
          LOADI   A, 1        ; i=1
          LOAD    D, [N]      ; register_D=N
Loop:     CMP     A, D        ; i<=N ?
          BRG     End         ; exit if i>N
Add:      ADD     B, A        ; sum+=i
          ADDI    A, 1        ; i++
          JUMP    Loop        ; next iteration
End:      STORE   [sum], B    ; write B to sum
```

Load the value of N into register D.

Add the numbers from 1 to 5

```c
// C Version
// using a for loop



int main()
{
        int N=5;
        int i, sum;

        sum=0;
        for(i=1; i<=N; i++) {
           sum+=i;
        }

        // printf("%d\n", sum);
}
```

```
; Assembly Version

.data
N         BYTE    5
i         BYTE    ?
sum       BYTE    ?

.code
          LOADI   B, 0        ; sum=0
          LOADI   A, 1        ; i=1
          LOAD    D, [N]      ; register_D=N
Loop:     CMP     A, D        ; i<=N ?
          BRG     End         ; exit if i>N
Add:      ADD     B, A        ; sum+=i
          ADDI    A, 1        ; i++
          JUMP    Loop        ; next iteration
End:      STORE   [sum], B    ; write B to sum
```

Add the numbers from 1 to 5

```c
// C Version
// using a for loop



int main()
{
        int N=5;
        int i, sum;

        sum=0;
        for(i=1; i<=N; i++) {
           sum+=i;
        }

        // printf("%d\n", sum);
}
```

```
; Assembly Version

.data
N         BYTE    5
i         BYTE    ?
sum       BYTE    ?

.code
          LOADI   B, 0        ; sum=0
          LOADI   A, 1        ; i=1
          LOAD    D, [N]      ; register_D=N
Loop:     CMP     A, D        ; i<=N ?
          BRG     End         ; exit if i>N
Add:      ADD     B, A        ; sum+=i
          ADDI    A, 1        ; i++
          JUMP    Loop        ; next iteration
End:      STORE   [sum], B    ; write B to sum
```

Add the numbers from 1 to 5

```c
// C Version
// using a for loop



int main()
{
        int N=5;
        int i, sum;

        sum=0;
        for(i=1; i<=N; i++) {
           sum+=i;
        }

        // printf("%d\n", sum);
}
```

```
; Assembly Version

.data
N         BYTE    5
i         BYTE    ?
sum       BYTE    ?

.code
          LOADI   B, 0        ; sum=0
          LOADI   A, 1        ; i=1
          LOAD    D, [N]      ; register_D=N
Loop:     CMP     A, D        ; i<=N ?
          BRG     End         ; exit if i>N
Add:      ADD     B, A        ; sum+=i
          ADDI    A, 1        ; i++
          JUMP    Loop        ; next iteration
End:      STORE   [sum], B    ; write B to sum
```

Add the numbers from 1 to 5

```c
// C Version
// using a for loop



int main()
{
        int N=5;
        int i, sum;

        sum=0;
        for(i=1; i<=N; i++) {
           sum+=i;
        }

        // printf("%d\n", sum);
}
```

```
; Assembly Version

.data
N         BYTE    5
i         BYTE    ?
sum       BYTE    ?

.code
          LOADI   B, 0        ; sum=0
          LOADI   A, 1        ; i=1
          LOAD    D, [N]      ; register_D=N
Loop:     CMP     A, D        ; i<=N ?
          BRG     End         ; exit if i>N
Add:      ADD     B, A        ; sum+=i
          ADDI    A, 1        ; i++
          JUMP    Loop        ; next iteration
End:      STORE   [sum], B    ; write B to sum
```

Add the numbers from 1 to 5

```c
// C Version
// using a for loop



int main()
{
        int N=5;
        int i, sum;

        sum=0;
        for(i=1; i<=N; i++) {
           sum+=i;
        }

        // printf("%d\n", sum);
}
```

i=2

```
; Assembly Version

.data
N         BYTE    5
i         BYTE    ?
sum       BYTE    ?

.code
          LOADI   B, 0        ; sum=0
          LOADI   A, 1        ; i=1
          LOAD    D, [N]      ; register_D=N
Loop:     CMP     A, D        ; i<=N ?
          BRG     End         ; exit if i>N
Add:      ADD     B, A        ; sum+=i
          ADDI    A, 1        ; i++
          JUMP    Loop        ; next iteration
End:      STORE   [sum], B    ; write B to sum
```

Add the numbers from 1 to 5

```c
// C Version
// using a for loop



int main()
{
        int N=5;
        int i, sum;

        sum=0;
        for(i=1; i<=N; i++) {
           sum+=i;
        }

        // printf("%d\n", sum);
}
```

```
; Assembly Version

.data
N         BYTE    5
i         BYTE    ?
sum       BYTE    ?

.code
          LOADI   B, 0        ; sum=0
          LOADI   A, 1        ; i=1
          LOAD    D, [N]      ; register_D=N
Loop:     CMP     A, D        ; i<=N ?
          BRG     End         ; exit if i>N
Add:      ADD     B, A        ; sum+=i
          ADDI    A, 1        ; i++
          JUMP    Loop        ; next iteration
End:      STORE   [sum], B    ; write B to sum
```

Add the numbers from 1 to 5

```c
// C Version
// using a for loop



int main()
{
        int N=5;
        int i, sum;

        sum=0;
        for(i=1; i<=N; i++) {
           sum+=i;
        }

        // printf("%d\n", sum);
}
```

```
; Assembly Version

.data
N         BYTE    5
i         BYTE    ?
sum       BYTE    ?

.code
          LOADI   B, 0        ; sum=0
          LOADI   A, 1        ; i=1
          LOAD    D, [N]      ; register_D=N
Loop:     CMP     A, D        ; i<=N ?
          BRG     End         ; exit if i>N
Add:      ADD     B, A        ; sum+=i
          ADDI    A, 1        ; i++
          JUMP    Loop        ; next iteration
End:      STORE   [sum], B    ; write B to sum
```

Add the numbers from 1 to 5

```c
// C Version
// using a for loop



int main()
{
        int N=5;
        int i, sum;

        sum=0;
        for(i=1; i<=N; i++) {
           sum+=i;
        }

        // printf("%d\n", sum);
}
```

```
; Assembly Version

.data
N         BYTE    5
i         BYTE    ?
sum       BYTE    ?

.code
          LOADI   B, 0        ; sum=0
          LOADI   A, 1        ; i=1
          LOAD    D, [N]      ; register_D=N
Loop:     CMP     A, D        ; i<=N ?
          BRG     End         ; exit if i>N
Add:      ADD     B, A        ; sum+=i
          ADDI    A, 1        ; i++
          JUMP    Loop        ; next iteration
End:      STORE   [sum], B    ; write B to sum
```

Add the numbers from 1 to 5

```c
// C Version
// using a for loop




int main()
{
        int N=5;
        int i, sum;

        sum=0;
        for(i=1; i<=N; i++) {
           sum+=i;
        }

        // printf("%d\n", sum);
}
```

i=3

```
; Assembly Version

.data
N         BYTE    5
i         BYTE    ?
sum       BYTE    ?

.code
          LOADI   B, 0        ; sum=0
          LOADI   A, 1        ; i=1
          LOAD    D, [N]      ; register_D=N
Loop:     CMP     A, D        ; i<=N ?
          BRG     End         ; exit if i>N
Add:      ADD     B, A        ; sum+=i
          ADDI    A, 1        ; i++
          JUMP    Loop        ; next iteration
End:      STORE   [sum], B    ; write B to sum
```

Add the numbers from 1 to 5

```c
// C Version
// using a for loop



int main()
{
        int N=5;
        int i, sum;

        sum=0;
        for(i=1; i<=N; i++) {
           sum+=i;
        }

        // printf("%d\n", sum);
}
```

```
; Assembly Version

.data
N         BYTE    5
i         BYTE    ?
sum       BYTE    ?

.code
          LOADI   B, 0        ; sum=0
          LOADI   A, 1        ; i=1
          LOAD    D, [N]      ; register_D=N
Loop:     CMP     A, D        ; i<=N ?
          BRG     End         ; exit if i>N
Add:      ADD     B, A        ; sum+=i
          ADDI    A, 1        ; i++
          JUMP    Loop        ; next iteration
End:      STORE   [sum], B    ; write B to sum
```

Add the numbers from 1 to 5

```c
// C Version
// using a for loop



int main()
{
        int N=5;
        int i, sum;

        sum=0;
        for(i=1; i<=N; i++) {
           sum+=i;
        }

        // printf("%d\n", sum);
}
```

```
; Assembly Version

.data
N         BYTE    5
i         BYTE    ?
sum       BYTE    ?

.code
          LOADI   B, 0        ; sum=0
          LOADI   A, 1        ; i=1
          LOAD    D, [N]      ; register_D=N
Loop:     CMP     A, D        ; i<=N ?
          BRG     End         ; exit if i>N
Add:      ADD     B, A        ; sum+=i
          ADDI    A, 1        ; i++
          JUMP    Loop        ; next iteration
End:      STORE   [sum], B    ; write B to sum
```

Add the numbers from 1 to 5

```c
// C Version
// using a for loop



int main()
{
        int N=5;
        int i, sum;

        sum=0;
        for(i=1; i<=N; i++) {
           sum+=i;
        }

        // printf("%d\n", sum);
}
```

```
; Assembly Version

.data
N         BYTE    5
i         BYTE    ?
sum       BYTE    ?

.code
          LOADI   B, 0        ; sum=0
          LOADI   A, 1        ; i=1
          LOAD    D, [N]      ; register_D=N
Loop:     CMP     A, D        ; i<=N ?
          BRG     End         ; exit if i>N
Add:      ADD     B, A        ; sum+=i
          ADDI    A, 1        ; i++
          JUMP    Loop        ; next iteration
End:      STORE   [sum], B    ; write B to sum
```

Add the numbers from 1 to 5

```c
// C Version
// using a for loop




int main()
{
        int N=5;
        int i, sum;

        sum=0;
        for(i=1; i<=N; i++) {
           sum+=i;
        }

        // printf("%d\n", sum);
}
```

i=4

```
; Assembly Version

.data
N         BYTE    5
i         BYTE    ?
sum       BYTE    ?

.code
          LOADI   B, 0        ; sum=0
          LOADI   A, 1        ; i=1
          LOAD    D, [N]      ; register_D=N
Loop:     CMP     A, D        ; i<=N ?
          BRG     End         ; exit if i>N
Add:      ADD     B, A        ; sum+=i
          ADDI    A, 1        ; i++
          JUMP    Loop        ; next iteration
End:      STORE   [sum], B    ; write B to sum
```

Add the numbers from 1 to 5

```c
// C Version
// using a for loop



int main()
{
        int N=5;
        int i, sum;

        sum=0;
        for(i=1; i<=N; i++) {
           sum+=i;
        }

        // printf("%d\n", sum);
}
```

```
; Assembly Version

.data
N         BYTE    5
i         BYTE    ?
sum       BYTE    ?

.code
          LOADI   B, 0        ; sum=0
          LOADI   A, 1        ; i=1
          LOAD    D, [N]      ; register_D=N
Loop:     CMP     A, D        ; i<=N ?
          BRG     End         ; exit if i>N
Add:      ADD     B, A        ; sum+=i
          ADDI    A, 1        ; i++
          JUMP    Loop        ; next iteration
End:      STORE   [sum], B    ; write B to sum
```

Add the numbers from 1 to 5

```c
// C Version
// using a for loop



int main()
{
        int N=5;
        int i, sum;

        sum=0;
        for(i=1; i<=N; i++) {
           sum+=i;
        }

        // printf("%d\n", sum);
}
```

```
; Assembly Version

.data
N         BYTE    5
i         BYTE    ?
sum       BYTE    ?

.code
          LOADI   B, 0        ; sum=0
          LOADI   A, 1        ; i=1
          LOAD    D, [N]      ; register_D=N
Loop:     CMP     A, D        ; i<=N ?
          BRG     End         ; exit if i>N
Add:      ADD     B, A        ; sum+=i
          ADDI    A, 1        ; i++
          JUMP    Loop        ; next iteration
End:      STORE   [sum], B    ; write B to sum
```

Add the numbers from 1 to 5

```c
// C Version
// using a for loop



int main()
{
        int N=5;
        int i, sum;

        sum=0;
        for(i=1; i<=N; i++) {
           sum+=i;
        }

        // printf("%d\n", sum);
}
```

```
; Assembly Version

.data
N         BYTE    5
i         BYTE    ?
sum       BYTE    ?

.code
          LOADI   B, 0        ; sum=0
          LOADI   A, 1        ; i=1
          LOAD    D, [N]      ; register_D=N
Loop:     CMP     A, D        ; i<=N ?
          BRG     End         ; exit if i>N
Add:      ADD     B, A        ; sum+=i
          ADDI    A, 1        ; i++
          JUMP    Loop        ; next iteration
End:      STORE   [sum], B    ; write B to sum
```

Add the numbers from 1 to 5

```c
// C Version
// using a for loop




int main()
{
        int N=5;
        int i, sum;

        sum=0;
        for(i=1; i<=N; i++) {
           sum+=i;
        }

        // printf("%d\n", sum);
}
```

i=5

```
; Assembly Version

.data
N         BYTE    5
i         BYTE    ?
sum       BYTE    ?

.code
          LOADI   B, 0        ; sum=0
          LOADI   A, 1        ; i=1
          LOAD    D, [N]      ; register_D=N
Loop:     CMP     A, D        ; i<=N ?
          BRG     End         ; exit if i>N
Add:      ADD     B, A        ; sum+=i
          ADDI    A, 1        ; i++
          JUMP    Loop        ; next iteration
End:      STORE   [sum], B    ; write B to sum
```

Add the numbers from 1 to 5

```c
// C Version
// using a for loop



int main()
{
        int N=5;
        int i, sum;

        sum=0;
        for(i=1; i<=N; i++) {
           sum+=i;
        }

        // printf("%d\n", sum);
}
```

```
; Assembly Version

.data
N         BYTE    5
i         BYTE    ?
sum       BYTE    ?

.code
          LOADI   B, 0        ; sum=0
          LOADI   A, 1        ; i=1
          LOAD    D, [N]      ; register_D=N
Loop:     CMP     A, D        ; i<=N ?
          BRG     End         ; exit if i>N
Add:      ADD     B, A        ; sum+=i
          ADDI    A, 1        ; i++
          JUMP    Loop        ; next iteration
End:      STORE   [sum], B    ; write B to sum
```

Add the numbers from 1 to 5

```c
// C Version
// using a for loop



int main()
{
        int N=5;
        int i, sum;

        sum=0;
        for(i=1; i<=N; i++) {
           sum+=i;
        }

        // printf("%d\n", sum);
}
```

```
; Assembly Version

.data
N         BYTE    5
i         BYTE    ?
sum       BYTE    ?

.code
          LOADI   B, 0        ; sum=0
          LOADI   A, 1        ; i=1
          LOAD    D, [N]      ; register_D=N
Loop:     CMP     A, D        ; i<=N ?
          BRG     End         ; exit if i>N
Add:      ADD     B, A        ; sum+=i
          ADDI    A, 1        ; i++
          JUMP    Loop        ; next iteration
End:      STORE   [sum], B    ; write B to sum
```

Add the numbers from 1 to 5

```c
// C Version
// using a for loop



int main()
{
        int N=5;
        int i, sum;

        sum=0;
        for(i=1; i<=N; i++) {
           sum+=i;
        }

        // printf("%d\n", sum);
}
```

```
; Assembly Version

.data
N         BYTE    5
i         BYTE    ?
sum       BYTE    ?

.code
          LOADI   B, 0        ; sum=0
          LOADI   A, 1        ; i=1
          LOAD    D, [N]      ; register_D=N
Loop:     CMP     A, D        ; i<=N ?
          BRG     End         ; exit if i>N
Add:      ADD     B, A        ; sum+=i
          ADDI    A, 1        ; i++
          JUMP    Loop        ; next iteration
End:      STORE   [sum], B    ; write B to sum
```

Add the numbers from 1 to 5

```
// C Version
// using a for loop




int main()
{
        int N=5;
        int i, sum;

        sum=0;
        for(i=1; i<=N; i++) {
           sum+=i;
        }

        // printf("%d\n", sum);
}
```

i=6

```
; Assembly Version

.data
N         BYTE    5
i         BYTE    ?
sum       BYTE    ?

.code
          LOADI   B, 0        ; sum=0
          LOADI   A, 1        ; i=1
          LOAD    D, [N]      ; register_D=N
Loop:     CMP     A, D        ; i<=N ?
          BRG     End         ; exit if i>N
Add:      ADD     B, A        ; sum+=i
          ADDI    A, 1        ; i++
          JUMP    Loop        ; next iteration
End:      STORE   [sum], B    ; write B to sum
```

Add the numbers from 1 to 5

```c
// C Version
// using a for loop



int main()
{
        int N=5;
        int i, sum;

        sum=0;
        for(i=1; i<=N; i++) {
           sum+=i;
        }

        // printf("%d\n", sum);
}
```

```
; Assembly Version

.data
N         BYTE    5
i         BYTE    ?
sum       BYTE    ?

.code
          LOADI   B, 0        ; sum=0
          LOADI   A, 1        ; i=1
          LOAD    D, [N]      ; register_D=N
Loop:     CMP     A, D        ; i<=N ?
          BRG     End         ; exit if i>N
Add:      ADD     B, A        ; sum+=i
          ADDI    A, 1        ; i++
          JUMP    Loop        ; next iteration
End:      STORE   [sum], B    ; write B to sum
```

For Loop Example:
Add the numbers from 1 to 5

Assembly Language v.s. Machine Language

i281 Assembly Code

```
.data
N         BYTE    5
i         BYTE    ?
sum       BYTE    ?

.code
          LOADI   B, 0          ; sum=0
          LOADI   A, 1          ; i=1
          LOAD    D, [N]        ; register_D=N
Loop:     CMP     A, D          ; i<=N ?
          BRG     End           ; exit if i>N
Add:      ADD     B, A          ; sum+=i
          ADDI    A, 1          ; i++
          JUMP    Loop          ; next iteration
End:      STORE   [sum], B      ; update the memory for sum
```

i281 Assembly Code

```
.data
N         BYTE    5
i         BYTE    ?
sum       BYTE    ?

.code
          LOADI   B, 0
          LOADI   A, 1
          LOAD    D, [N]
Loop:     CMP     A, D
          BRG     End
Add:      ADD     B, A
          ADDI    A, 1
          JUMP    Loop
End:      STORE   [sum], B
```

Mapping Assembly to Machine Code

```
.data
N         BYTE    5
i         BYTE    ?
sum       BYTE    ?

.code
          LOADI   B, 0
          LOADI   A, 1
          LOAD    D, [N]
Loop:     CMP     A, D
          BRG     End
Add:      ADD     B, A
          ADDI    A, 1
          JUMP    Loop
End:      STORE   [sum], B
```

Assembly Language

```
Data Memory:
00000101
00000000
00000000

Code Memory:
0011010000000000
0011000000000001
1000110000000000
1101001100000000
1111001000000011
0100010000000000
0101000000000001
1110000011111011
1010010000000010
```

Machine Language

Mapping Assembly to Machine Code

```
.data
N         BYTE    5
i         BYTE    ?
sum       BYTE    ?

.code
          LOADI   B, 0
          LOADI   A, 1
          LOAD    D, [N]
Loop:     CMP     A, D
          BRG     End
Add:      ADD     B, A
          ADDI    A, 1
          JUMP    Loop
End:      STORE   [sum], B
```

Assembly Language

Data Memory:

```
00000101
00000000
00000000
```

Code Memory:

```
00110100_00000000
00110000_00000001
10001100_00000000
11010011_00000000
11110010_00000011
01000100_00000000
01010000_00000001
11100000_11111011
10100100_00000010
```

Machine Language

Mapping Assembly to Machine Code

```
.data
N         BYTE    5
i         BYTE    ?
sum       BYTE    ?

.code
          LOADI   B, 0
          LOADI   A, 1
          LOAD    D, [N]
Loop:     CMP     A, D
          BRG     End
Add:      ADD     B, A
          ADDI    A, 1
          JUMP    Loop
End:      STORE   [sum], B
```

Assembly Language

```
Data Memory:
00000101
00000000
00000000

Code Memory:
0011_01_00_00000000
0011_00_00_00000001
1000_11_00_00000000
1101_00_11_00000000
1111_00_10_00000011
0100_01_00_00000000
0101_00_00_00000001
1110_00_00_11111011
1010_01_00_00000010
```

Machine Language

Mapping Assembly to Machine Code

```
.data
N         BYTE    5
i         BYTE    ?
sum       BYTE    ?

.code
          LOADI   B, 0
          LOADI   A, 1
          LOAD    D, [N]
Loop:     CMP     A, D
          BRG     End
Add:      ADD     B, A
          ADDI    A, 1
          JUMP    Loop
End:      STORE   [sum], B
```

Data Memory:

```
00000101
00000000
00000000
```

Code Memory:

```
0011_01_00_00000000
0011_00_00_00000001
1000_11_00_00000000
1101_00_11_00000000
1111_00_10_00000011
0100_01_00_00000000
0101_00_00_00000001
1110_00_00_11111011
1010_01_00_00000010
```

Mapping Assembly to Machine Code

```
.data
N         BYTE    5
i         BYTE    ?
sum       BYTE    ?

.code
          LOADI   B, 0
          LOADI   A, 1
          LOAD    D, [N]
Loop:     CMP     A, D
          BRG     End
Add:      ADD     B, A
          ADDI    A, 1
          JUMP    Loop
End:      STORE   [sum], B
```

Data Memory:

```
00000101
00000000
00000000
```

Code Memory:

```
0011_01_00_00000000
0011_00_00_00000001
1000_11_00_00000000
1101_00_11_00000000
1111_00_10_00000011
0100_01_00_00000000
0101_00_00_00000001
1110_00_00_11111011
1010_01_00_00000010
```

Mapping Assembly to Machine Code

```
.data
N         BYTE    5
i         BYTE    ?
sum       BYTE    ?

.code
          LOADI   B, 0
          LOADI   A, 1
          LOAD    D, [N]
Loop:     CMP     A, D
          BRG     End
Add:      ADD     B, A
          ADDI    A, 1
          JUMP    Loop
End:      STORE   [sum], B
```

Data Memory:

```
00000101
00000000
00000000
```

Code Memory:

```
0011_01_00_00000000
0011_00_00_00000001
1000_11_00_00000000
1101_00_11_00000000
1111_00_10_00000011
0100_01_00_00000000
0101_00_00_00000001
1110_00_00_11111011
1010_01_00_00000010
```

Mapping Assembly to Machine Code

```
.data
N         BYTE    5
i         BYTE    ?
sum       BYTE    ?

.code
          LOADI   B, 0
          LOADI   A, 1
          LOAD    D, [N]
Loop:     CMP     A, D
          BRG     End
Add:      ADD     B, A
          ADDI    A, 1
          JUMP    Loop
End:      STORE   [sum], B
```

Data Memory:

```
00000101
00000000
00000000
```

Code Memory:

```
0011_01_00_00000000
0011_00_00_00000001
1000_11_00_00000000
1101_00_11_00000000
1111_00_10_00000011
0100_01_00_00000000
0101_00_00_00000001
1110_00_00_11111011
1010_01_00_00000010
```

OPCODE Mapping

```
.data
N       BYTE    5
i       BYTE    ?
sum     BYTE    ?

.code
        LOADI   B, 0
        LOADI   A, 1
        LOAD    D, [N]
Loop:   CMP     A, D
        BRG     End
Add:    ADD     B, A
        ADDI    A, 1
        JUMP    Loop
End:    STORE   [sum], B
```

Data Memory:

```
00000101
00000000
00000000
```

Code Memory:

```
0011_01_00_00000000
0011_00_00_00000001
1000_11_00_00000000
1101_00_11_00000000
1111_00_10_00000011
0100_01_00_00000000
0101_00_00_00000001
1110_00_00_11111011
1010_01_00_00000010
```

OPCODE Mapping

```
.data
N       BYTE    5
i       BYTE    ?
sum     BYTE    ?

.code
        LOADI   B, 0
        LOADI   A, 1
        LOAD    D, [N]
Loop:   CMP     A, D
        BRG     End
Add:    ADD     B, A
        ADDI    A, 1
        JUMP    Loop
End:    STORE   [sum], B
```

Data Memory:

```
00000101
00000000
00000000
```

Code Memory:

```
0011_01_00_00000000
0011_00_00_00000001
1000_11_00_00000000
1101_00_11_00000000
1111_00_10_00000011
0100_01_00_00000000
0101_00_00_00000001
1110_00_00_11111011
1010_01_00_00000010
```

Register Parameter Mapping

```
.data
N       BYTE    5
i       BYTE    ?
sum     BYTE    ?

.code
        LOADI   B, 0
        LOADI   A, 1
        LOAD    D, [N]
Loop:   CMP     A, D
        BRG     End
Add:    ADD     B, A
        ADDI    A, 1
        JUMP    Loop
End:    STORE   [sum], B
```

Data Memory:

```
00000101
00000000
00000000
```

Code Memory:

```
0011_01_00_00000000
0011_00_00_00000001
1000_11_00_00000000
1101_00_11_00000000
1111_00_10_00000011
0100_01_00_00000000
0101_00_00_00000001
1110_00_00_11111011
1010_01_00_00000010
```

Register Parameter Mapping

```
.data
N       BYTE    5
i       BYTE    ?
sum     BYTE    ?

.code
        LOADI   B, 0
        LOADI   A, 1
        LOAD    D, [N]
Loop:   CMP     A, D
        BRG     End
Add:    ADD     B, A
        ADDI    A, 1
        JUMP    Loop
End:    STORE   [sum], B
```

Data Memory:

```
00000101
00000000
00000000
```

Code Memory:

```
0011_01_00_00000000
0011_00_00_00000001
1000_11_00_00000000
1101_00_11_00000000
1111_00_10_00000011
0100_01_00_00000000
0101_00_00_00000001
1110_00_00_11111011
1010_01_00_00000010
```

Second Register Parameter Mapping

```
.data
N       BYTE    5
i       BYTE    ?
sum     BYTE    ?

.code
        LOADI   B, 0
        LOADI   A, 1
        LOAD    D, [N]
Loop:   CMP     A, D
        BRG     End
Add:    ADD     B, A
        ADDI    A, 1
        JUMP    Loop
End:    STORE   [sum], B
```

Data Memory:

```
00000101
00000000
00000000
```

Code Memory:

```
0011_01_00_00000000
0011_00_00_00000001
1000_11_00_00000000
1101_00_11_00000000
1111_00_10_00000011
0100_01_00_00000000
0101_00_00_00000001
1110_00_00_11111011
1010_01_00_00000010
```

Second Register Parameter Mapping

```
.data
N       BYTE    5
i       BYTE    ?
sum     BYTE    ?

.code
        LOADI   B, 0
        LOADI   A, 1
        LOAD    D, [N]
Loop:   CMP     A, D
        BRG     End
Add:    ADD     B, A
        ADDI    A, 1
        JUMP    Loop
End:    STORE   [sum], B
```

Data Memory:

```
00000101
00000000
00000000
```

Code Memory:

```
0011_01_00_00000000
0011_00_00_00000001
1000_11_00_00000000
1101_00_11_00000000
1111_00_10_00000011
0100_01_00_00000000
0101_00_00_00000001
1110_00_00_11111011
1010_01_00_00000010
```

Value / Address / Offset Mapping

```
.data
N       BYTE    5
i       BYTE    ?
sum     BYTE    ?

.code
        LOADI   B, 0
        LOADI   A, 1
        LOAD    D, [N]
Loop:   CMP     A, D
        BRG     End
Add:    ADD     B, A
        ADDI    A, 1
        JUMP    Loop
End:    STORE   [sum], B
```

Data Memory:

```
00000101
00000000
00000000
```

Code Memory:

```
0011_01_00_00000000
0011_00_00_00000001
1000_11_00_00000000
1101_00_11_00000000
1111_00_10_00000011
0100_01_00_00000000
0101_00_00_00000001
1110_00_00_11111011
1010_01_00_00000010
```

Value / Address / Offset Mapping

```
.data
N       BYTE    5
i       BYTE    ?
sum     BYTE    ?

.code
        LOADI   B, 0
        LOADI   A, 1
        LOAD    D, [N]
Loop:   CMP     A, D
        BRG     End
Add:    ADD     B, A
        ADDI    A, 1
        JUMP    Loop
End:    STORE   [sum], B
```

Data Memory:

```
00000101
00000000
00000000
```

Code Memory:

```
0011_01_00_00000000
0011_00_00_00000001
1000_11_00_00000000
1101_00_11_00000000
1111_00_10_00000011
0100_01_00_00000000
0101_00_00_00000001
1110_00_00_11111011
1010_01_00_00000010
```

“Don’t care” bits …

```
.data
N         BYTE    5
i         BYTE    ?
sum       BYTE    ?

.code
          LOADI   B, 0
          LOADI   A, 1
          LOAD    D, [N]
Loop:     CMP     A, D
          BRG     End
Add:      ADD     B, A
          ADDI    A, 1
          JUMP    Loop
End:      STORE   [sum], B
```

```
Data Memory:
00000101
00000000
00000000

Code Memory:
0011_01_dd_00000000
0011_00_dd_00000001
1000_11_dd_00000000
1101_00_11_dddddddd
1111_dd_10_00000011
0100_01_00_dddddddd
0101_00_dd_00000001
1110_dd_dd_11111011
1010_01_dd_00000010
```

… are mapped to 0 by the Assembler

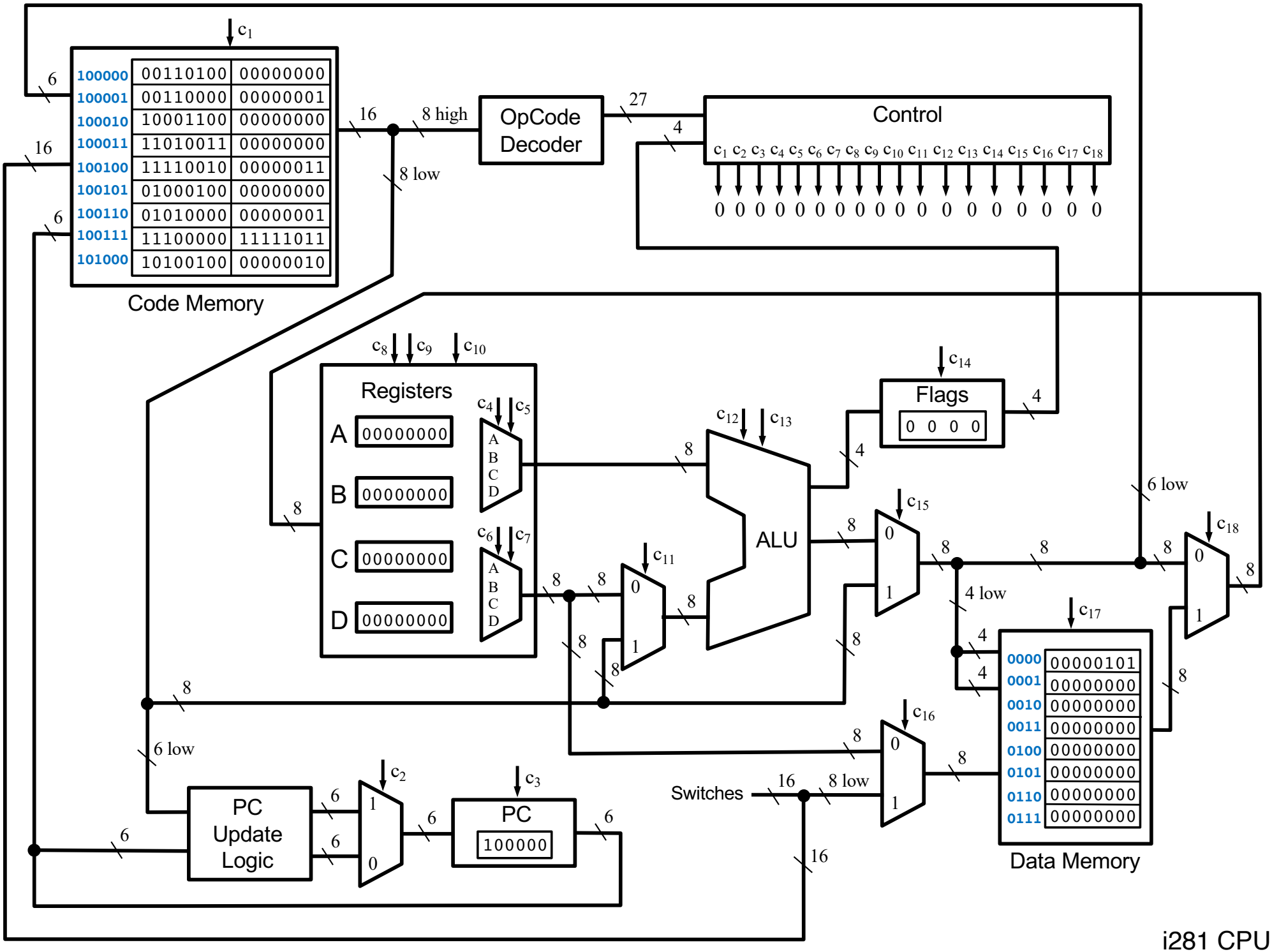
```
.data
N       BYTE    5
i       BYTE    ?
sum     BYTE    ?

.code
        LOADI   B, 0
        LOADI   A, 1
        LOAD    D, [N]
Loop:   CMP     A, D
        BRG     End
Add:    ADD     B, A
        ADDI    A, 1
        JUMP    Loop
End:    STORE   [sum], B
```

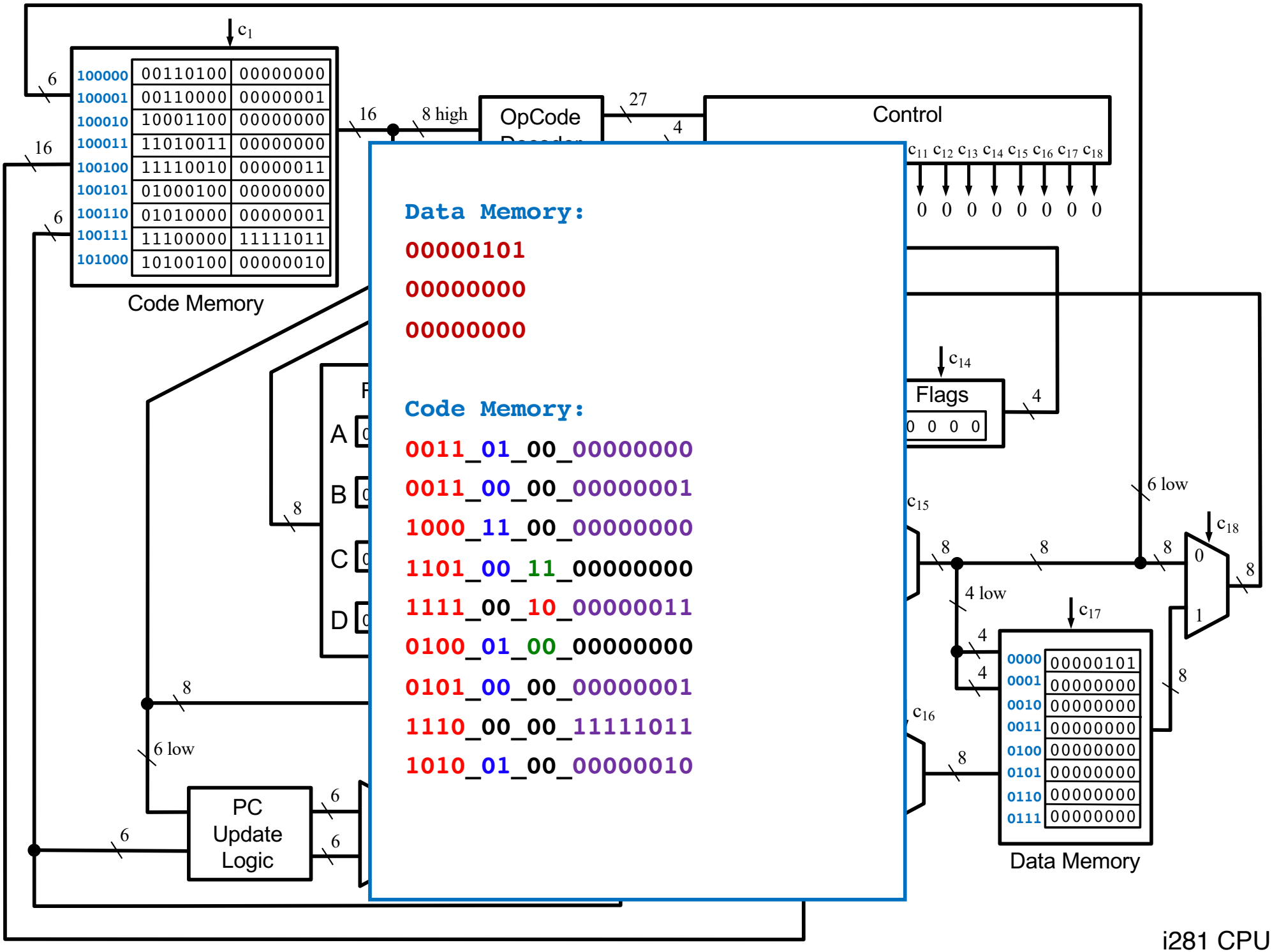
```
Data Memory:
00000101
00000000
00000000

Code Memory:
0011_01_00_00000000
0011_00_00_00000001
1000_11_00_00000000
1101_00_11_00000000
1111_00_10_00000011
0100_01_00_00000000
0101_00_00_00000001
1110_00_00_11111011
1010_01_00_00000010
```

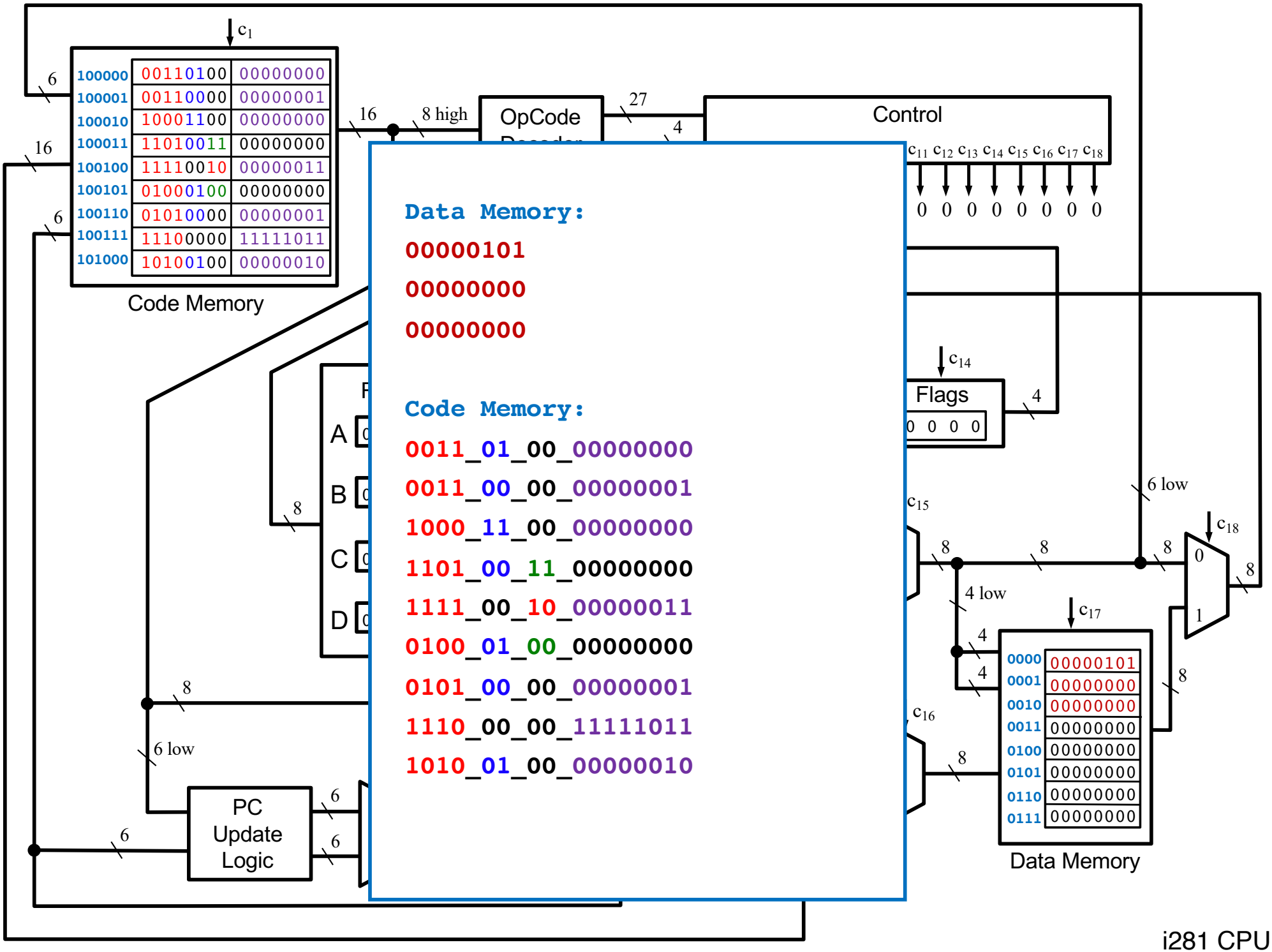
Mapping Assembly to Machine Code

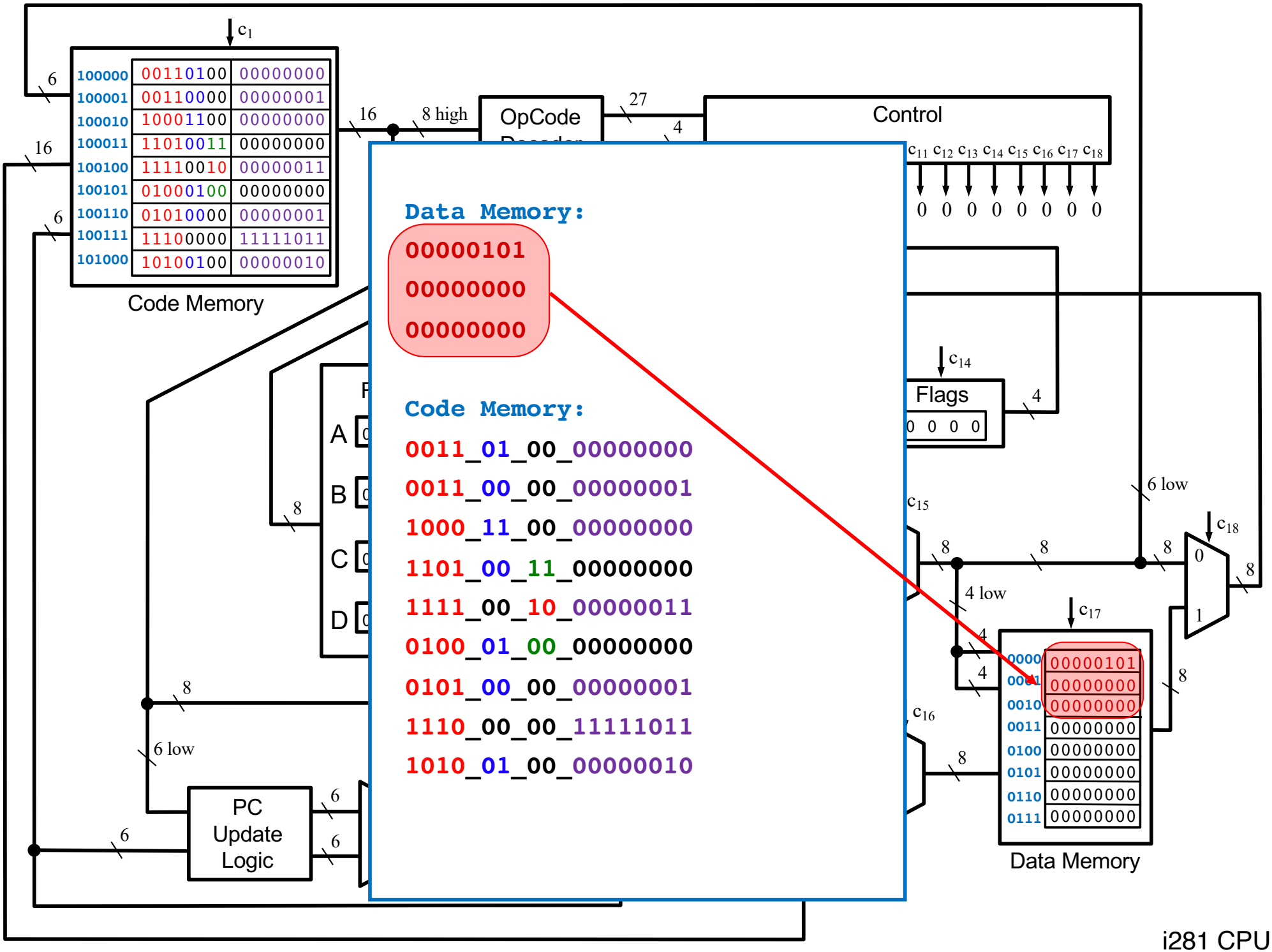
```
.data
N       BYTE    5
i       BYTE    ?
sum     BYTE    ?

.code
        LOADI   B, 0
        LOADI   A, 1
        LOAD    D, [N]
Loop:   CMP     A, D
        BRG     End
Add:    ADD     B, A
        ADDI    A, 1
        JUMP    Loop
End:    STORE   [sum], B
```

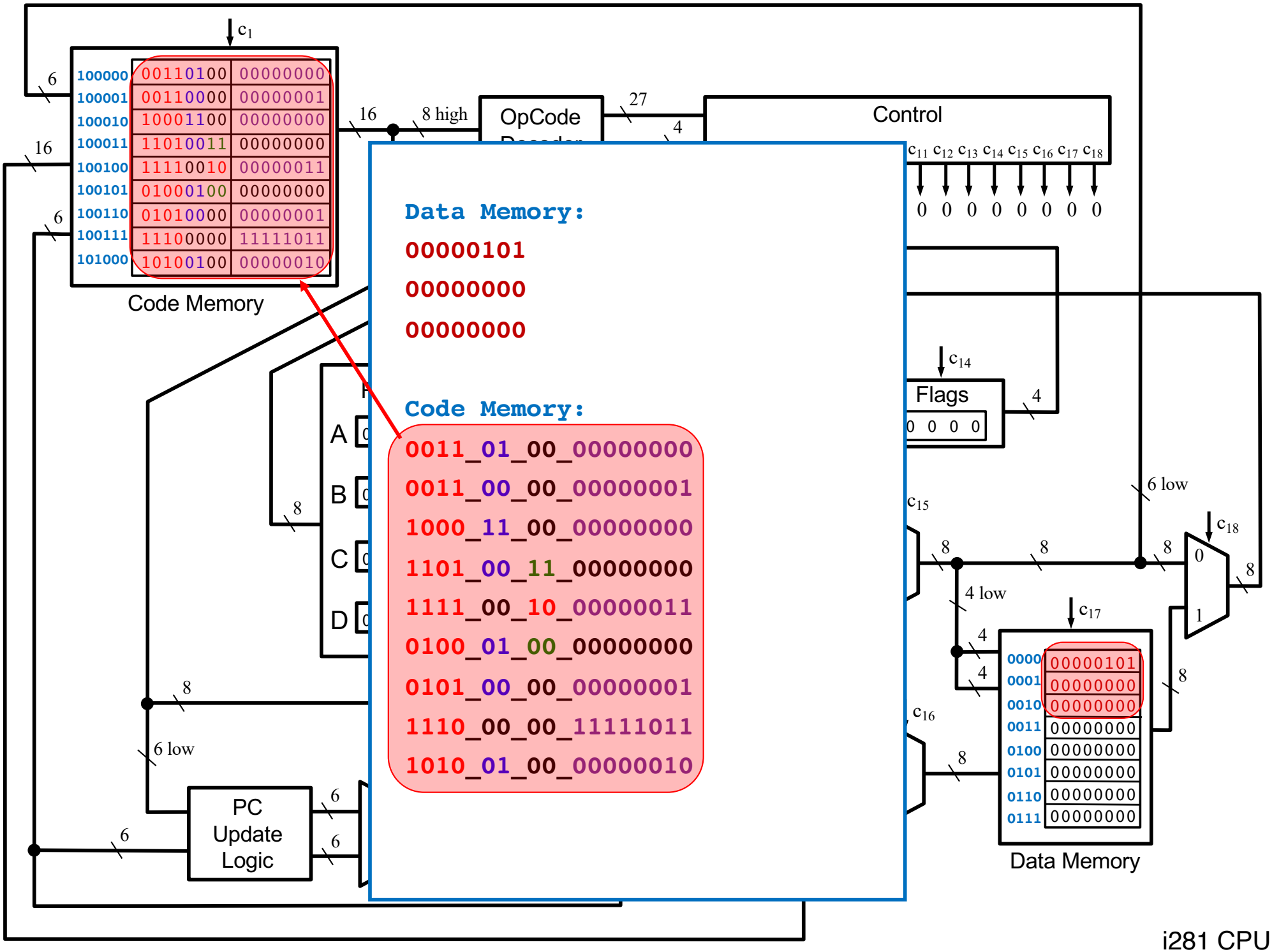
```
Data Memory:
00000101
00000000
00000000

Code Memory:
0011_01_00_00000000
0011_00_00_00000001
1000_11_00_00000000
1101_00_11_00000000
1111_00_10_00000011
0100_01_00_00000000
0101_00_00_00000001
1110_00_00_11111011
1010_01_00_00000010
```

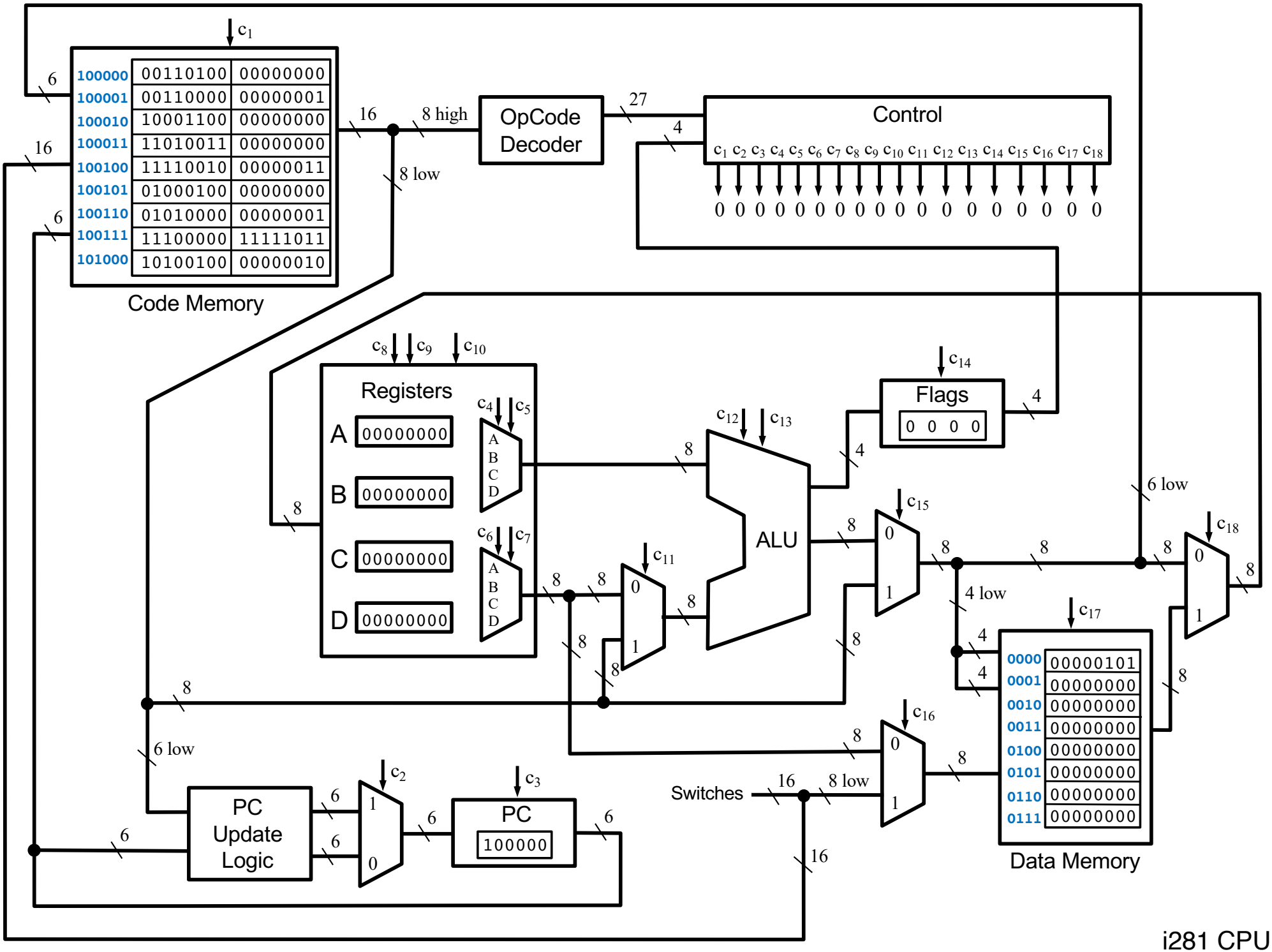

c1
6
100000 00110100 00000000
100001 00110000 00000001
100010 10001100 00000000
100011 11010011 00000000
100100 11110010 00000011
100101 01000100 00000000
100110 01010000 00000001
100111 11100000 11111011
101000 10100100 00000010
Code Memory
16
8 high
8 low
OpCode Decoder
27
4
Control
c1 c2 c3 c4 c5 c6 c7 c8 c9 c10 c11 c12 c13 c14 c15 c16 c17 c18
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
c8 c9 c10
Registers
A 00000000
B 00000000
C 00000000
D 00000000
c4 c5
c6 c7
A B C D
8
c14
Flags
0 0 0 0
4
c12 c13
ALU
c11
c15
c18
6 low
4 low
c17
0000 00000101
0001 00000000
0010 00000000
0011 00000000
0100 00000000
0101 00000000
0110 00000000
0111 00000000
Data Memory
c16
Switches
8 low
c2
c3
PC Update Logic
PC
100000
i281 CPU


c1
6
100000 00110100 00000000
100001 00110000 00000001
100010 10001100 00000000
100011 11010011 00000000
100100 11110010 00000011
100101 01000100 00000000
100110 01010000 00000001
100111 11100000 11111011
101000 10100100 00000010
Code Memory
16
8 high
OpCode
27
4
Control
c11 c12 c13 c14 c15 c16 c17 c18
0 0 0 0 0 0 0 0
16
6
6
Data Memory:
00000101
00000000
00000000
Code Memory:
0011_01_00_00000000
0011_00_00_00000001
1000_11_00_00000000
1101_00_11_00000000
1111_00_10_00000011
0100_01_00_00000000
0101_00_00_00000001
1110_00_00_11111011
1010_01_00_00000010
c14
Flags
4
0 0 0 0
A
B
C
D
8
c15
8
8
8
6 low
c18
0
1
8
4 low
c17
4
4
8
0000 00000101
0001 00000000
0010 00000000
0011 00000000
0100 00000000
0101 00000000
0110 00000000
0111 00000000
Data Memory
c16
8
8
6 low
PC
Update
Logic
6
6
6
6
i281 CPU


c1
100000 00110100 00000000
100001 00110000 00000001
100010 10001100 00000000
100011 11010011 00000000
100100 11110010 00000011
100101 01000100 00000000
100110 01010000 00000001
100111 11100000 11111011
101000 10100100 00000010
Code Memory
6
16
8 high
OpCode
27
4
Control
c11 c12 c13 c14 c15 c16 c17 c18
0 0 0 0 0 0 0 0
Data Memory:
00000101
00000000
00000000
Code Memory:
0011_01_00_00000000
0011_00_00_00000001
1000_11_00_00000000
1101_00_11_00000000
1111_00_10_00000011
0100_01_00_00000000
0101_00_00_00000001
1110_00_00_11111011
1010_01_00_00000010
A
B
C
D
8
c14
Flags
0 0 0 0
4
6 low
c15
8
c18
0
1
4 low
c17
0000 00000101
0001 00000000
0010 00000000
0011 00000000
0100 00000000
0101 00000000
0110 00000000
0111 00000000
Data Memory
c16
6 low
PC
Update
Logic
i281 CPU


c1
100000 00110100 00000000
100001 00110000 00000001
100010 10001100 00000000
100011 11010011 00000000
100100 11110010 00000011
100101 01000100 00000000
100110 01010000 00000001
100111 11100000 11111011
101000 10100100 00000010
Code Memory
6
16
8 high
OpCode
27
4
Control
c11 c12 c13 c14 c15 c16 c17 c18
0 0 0 0 0 0 0 0
Data Memory:
00000101
00000000
00000000
Code Memory:
0011_01_00_00000000
0011_00_00_00000001
1000_11_00_00000000
1101_00_11_00000000
1111_00_10_00000011
0100_01_00_00000000
0101_00_00_00000001
1110_00_00_11111011
1010_01_00_00000010
c14
Flags
0 0 0 0
4
A
B
C
D
8
6 low
c15
c18
4 low
c17
0000 00000101
0001 00000000
0010 00000000
0011 00000000
0100 00000000
0101 00000000
0110 00000000
0111 00000000
Data Memory
c16
PC
Update
Logic
i281 CPU


c1
6
100000 00110100 00000000
100001 00110000 00000001
100010 10001100 00000000
100011 11010011 00000000
100100 11110010 00000011
100101 01000100 00000000
100110 01010000 00000001
100111 11100000 11111011
101000 10100100 00000010
Code Memory
16
8 high
OpCode
27
4
Control
c11 c12 c13 c14 c15 c16 c17 c18
0 0 0 0 0 0 0 0
16
6
Data Memory:
00000101
00000000
00000000
Code Memory:
0011_01_00_00000000
0011_00_00_00000001
1000_11_00_00000000
1101_00_11_00000000
1111_00_10_00000011
0100_01_00_00000000
0101_00_00_00000001
1110_00_00_11111011
1010_01_00_00000010
A
B
C
D
8
c14
Flags
4
0 0 0 0
6 low
c15
8
8
8
c18
0
1
8
4 low
c17
4
4
0000 00000101
0001 00000000
0010 00000000
0011 00000000
0100 00000000
0101 00000000
0110 00000000
0111 00000000
8
c16
8
Data Memory
8
6 low
PC
Update
Logic
6
6
6
6
i281 CPU


c1
6
100000 00110100 00000000
100001 00110000 00000001
100010 10001100 00000000
100011 11010011 00000000
100100 11110010 00000011
100101 01000100 00000000
100110 01010000 00000001
100111 11100000 11111011
101000 10100100 00000010
Code Memory
16
8 high
8 low
OpCode Decoder
27
4
Control
c1 c2 c3 c4 c5 c6 c7 c8 c9 c10 c11 c12 c13 c14 c15 c16 c17 c18
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
c8 c9 c10
Registers
A 00000000
B 00000000
C 00000000
D 00000000
c4 c5
c6 c7
A B C D
8
c14
Flags
0 0 0 0
4
c12 c13
ALU
c11
c15
c18
6 low
4 low
c17
0000 00000101
0001 00000000
0010 00000000
0011 00000000
0100 00000000
0101 00000000
0110 00000000
0111 00000000
Data Memory
c16
Switches
8 low
c2
c3
PC Update Logic
PC
100000
i281 CPU

Do Loop Example:
Add the numbers from 1 to 5

C Version

```
// Add the numbers from 1 to 5 using a do loop.


int N=5;

int main()
{
        int i, sum;

        i=0;
        sum=0;

        do
        {
            i++;
            sum+=i;
        }while( i < N );
}
```

Assembly Version

```
; Add the numbers from 1 to 5 using a do loop.

.data
N       BYTE      5
sum     BYTE      ?

.code
        LOADI A, 0              ; i = 0
        LOADI B, 0              ; sum=0
        LOAD D, [N]             ; register D = N
Do:     ADDI A, 1               ; i++
        ADD B, A                ; sum+=i
        CMP D, A                ; N > i ? (register ordering is swapped)
        BRG Do                  ; if true, jump to Do
End:    STORE [sum], B          ; store sum to memory

; Register allocation:
; A: i  (the variable i is optimized to register A)
; B: sum
; C: <not used>
; D: N
```

Do Loop

```
// Add the numbers from
// 1 to 5 using a do loop
int N=5;

int main()
{
        int i, sum;

        i=0;
        sum=0;

        do
        {
            i++;
            sum+=i;
        }while( i < N );
}
```

```
; assembly version

.data
N       BYTE      5
sum     BYTE      ?

.code
        LOADI A, 0              ; i = 0
        LOADI B, 0              ; sum=0
        LOAD D, [N]             ; register D = N
Do:     ADDI A, 1               ; i++
        ADD B, A                ; sum+=i
        CMP D, A                ; N > i ?
        BRG Do                  ; if true, jump to Do
End:    STORE [sum], B          ; store sum to memory

; Register allocation:
; A: i  (the variable i is optimized to register A)
; B: sum
; C: <not used>
; D: N
```

Machine Code Version

Data Memory:

```
00000101
00000000
```

Code Memory:

```
0011000000000000
0011010000000000
1000110000000000
0101000000000001
0100010000000000
1101110000000000
1111001011111100
1010010000000001
```

Assembly v.s. Machine Code

```
.data
N       BYTE      5
sum     BYTE      ?

.code
        LOADI   A, 0
        LOADI   B, 0
        LOAD    D, [N]
Do:     ADDI    A, 1
        ADD     B, A
        CMP     D, A
        BRG     Do
End:    STORE   [sum], B
```

Data Memory:

```
00000101
00000000
```

Code Memory:

```
0011000000000000
0011010000000000
1000110000000000
0101000000000001
0100010000000000
1101110000000000
1111001011111100
1010010000000001
```

Assembly v.s. Machine Code

```
.data
N       BYTE      5
sum     BYTE      ?

.code
        LOADI   A, 0
        LOADI   B, 0
        LOAD    D, [N]
Do:     ADDI    A, 1
        ADD     B, A
        CMP     D, A
        BRG     Do
End:    STORE   [sum], B
```

Data Memory:

```
00000101
00000000
```

Code Memory:

```
00110000_00000000
00110100_00000000
10001100_00000000
01010000_00000001
01000100_00000000
11011100_00000000
11110010_11111100
10100100_00000001
```

Assembly v.s. Machine Code

```
.data
N       BYTE      5
sum     BYTE      ?

.code
        LOADI   A, 0
        LOADI   B, 0
        LOAD    D, [N]
Do:     ADDI    A, 1
        ADD     B, A
        CMP     D, A
        BRG     Do
End:    STORE   [sum], B
```

Data Memory:

```
00000101
00000000
```

Code Memory:

```
0011_00_00_00000000
0011_01_00_00000000
1000_11_00_00000000
0101_00_00_00000001
0100_01_00_00000000
1101_11_00_00000000
1111_00_10_11111100
1010_01_00_00000001
```

Assembly v.s. Machine Code

```
.data
N       BYTE      5
sum     BYTE      ?

.code
        LOADI   A, 0
        LOADI   B, 0
        LOAD    D, [N]
Do:     ADDI    A, 1
        ADD     B, A
        CMP     D, A
        BRG     Do
End:    STORE   [sum], B
```

```
Data Memory:
00000101
00000000

Code Memory:
0011_00_00_00000000
0011_01_00_00000000
1000_11_00_00000000
0101_00_00_00000001
0100_01_00_00000000
1101_11_00_00000000
1111_00_10_11111100
1010_01_00_00000001
```

Assembly v.s. Machine Code

```
.data
N       BYTE      5
sum     BYTE      ?

.code
        LOADI   A, 0
        LOADI   B, 0
        LOAD    D, [N]
Do:     ADDI    A, 1
        ADD     B, A
        CMP     D, A
        BRG     Do
End:    STORE   [sum], B
```

Data Memory:

```
00000101
00000000
```

Code Memory:

```
0011_00_00_00000000
0011_01_00_00000000
1000_11_00_00000000
0101_00_00_00000001
0100_01_00_00000000
1101_11_00_00000000
1111_00_10_11111100
1010_01_00_00000001
```

Assembly v.s. Machine Code

```
.data
N       BYTE      5
sum     BYTE      ?

.code
        LOADI   A, 0
        LOADI   B, 0
        LOAD    D, [N]
Do:     ADDI    A, 1
        ADD     B, A
        CMP     D, A
        BRG     Do
End:    STORE   [sum], B
```

```
Data Memory:
00000101
00000000

Code Memory:
0011_00_00_00000000
0011_01_00_00000000
1000_11_00_00000000
0101_00_00_00000001
0100_01_00_00000000
1101_11_00_00000000
1111_00_10_11111100
1010_01_00_00000001
```

Assembly v.s. Machine Code

```
.data
N       BYTE      5
sum     BYTE      ?

.code
        LOADI   A, 0
        LOADI   B, 0
        LOAD    D, [N]
Do:     ADDI    A, 1
        ADD     B, A
        CMP     D, A
        BRG     Do
End:    STORE   [sum], B
```

```
Data Memory:
00000101
00000000

Code Memory:
0011_00_00_00000000
0011_01_00_00000000
1000_11_00_00000000
0101_00_00_00000001
0100_01_00_00000000
1101_11_00_00000000
1111_00_10_11111100
1010_01_00_00000001
```

Assembly v.s. Machine Code

```
.data
N       BYTE      5
sum     BYTE      ?

.code
        LOADI   A, 0
        LOADI   B, 0
        LOAD    D, [N]
Do:     ADDI    A, 1
        ADD     B, A
        CMP     D, A
        BRG     Do
End:    STORE   [sum], B
```

```
Data Memory:
00000101
00000000

Code Memory:
0011_00_00_00000000
0011_01_00_00000000
1000_11_00_00000000
0101_00_00_00000001
0100_01_00_00000000
1101_11_00_00000000
1111_00_10_11111100
1010_01_00_00000001
```

Assembly v.s. Machine Code

```
.data
N       BYTE      5
sum     BYTE      ?

.code
        LOADI   A, 0
        LOADI   B, 0
        LOAD    D, [N]
Do:     ADDI    A, 1
        ADD     B, A
        CMP     D, A
        BRG     Do
End:    STORE   [sum], B
```

```
Data Memory:
00000101
00000000

Code Memory:
0011_00_00_00000000
0011_01_00_00000000
1000_11_00_00000000
0101_00_00_00000001
0100_01_00_00000000
1101_11_00_00000000
1111_00_10_11111100
1010_01_00_00000001
```

Assembly v.s. Machine Code

```
.data
N       BYTE      5
sum     BYTE      ?

.code
        LOADI   A, 0
        LOADI   B, 0
        LOAD    D, [N]
Do:     ADDI    A, 1
        ADD     B, A
        CMP     D, A
        BRG     Do
End:    STORE   [sum], B
```

```
Data Memory:
00000101
00000000

Code Memory:
0011_00_dd_00000000
0011_01_dd_00000000
1000_11_dd_00000000
0101_00_dd_00000001
0100_01_00_dddddddd
1101_11_00_dddddddd
1111_dd_10_11111100
1010_01_dd_00000001
```

Assembly v.s. Machine Code

```
.data
N       BYTE      5
sum     BYTE      ?

.code
        LOADI   A, 0
        LOADI   B, 0
        LOAD    D, [N]
Do:     ADDI    A, 1
        ADD     B, A
        CMP     D, A
        BRG     Do
End:    STORE   [sum], B
```

```
Data Memory:
00000101
00000000

Code Memory:
0011_00_00_00000000
0011_01_00_00000000
1000_11_00_00000000
0101_00_00_00000001
0100_01_00_00000000
1101_11_00_00000000
1111_00_10_11111100
1010_01_00_00000001
```

While Loop Example:
Add the numbers from 1 to 5

While Loop

```
// Add the numbers from
// 1 to 5 using a while loop
int N=5;
int sum;
int i;

int main()
{
        i=1;
        sum=0;

        while( i <= N )
        {
                sum+=i;
                i++;
        }
}
```

```
; assembly version
.data
N       BYTE    5
sum     BYTE    ?
; i is optimized to register A

.code
        LOADI A, 1          ; i = 1
        LOADI B, 0          ; sum=0
        LOAD  D, [N]        ; register D = N
While:  CMP   A, D          ; i <= N ?
        BRG   End           ; if no, exit the loop
        ADD   B, A          ; sum+=i
        ADDI  A, 1          ; i++
        JUMP  While         ; next iteration
End:    STORE [sum], B      ; store sum to memory

; Register allocation:
; A: i
; B: sum
; C: <not used>
; D: N
```

Bubble Sort

C Version

```
int array[] = {7, 3, 2, 1, 6, 4, 5, 8};
int last = 7; // last valid index in the array
int temp;
int i, j;

int main()
{
   for (i = 0; i < last; i++)
        for (j = 0; j < last-i; j++)
               if (array[j] > array[j+1]){
                      temp = array[j];
                      array[j] = array[j+1];
                      array[j+1] = temp;
               }

   //for(i = 0; i < N; i++){
   //    printf("%d, ", array[i]);
   //}
}
```

Assembly Version

```
.data
array   BYTE 7, 3, 2, 1, 6, 4, 5, 8
last    BYTE 7
temp    BYTE ?

.code
        LOADI  A, 0                 ; i = 0;
Outer:  LOAD   D, [last]            ; Load last into D
        LOADI  B, 0                 ; j = 0;
        CMP    A, D                 ; i < last
        BRGE   End                  ; If i >= last break out of the outer loop
Inner:  LOAD   D, [last]            ; Re-Load last into D (this register is shared)
        SUB    D, A                 ; D = D - A  (i.e., D = last - i)
        CMP    B, D                 ; j < last - i
        BRGE   Iinc                 ; If j >= last-i  branch to Iinc
If:     LOADF  C, [array+B]         ; C = array[j]
        LOADF  D, [array+B+1]       ; D = array[j+1] (compiler adds 1 to addr. of array)
        CMP    D, C                 ; if array[j+1] < array[j]  (switched direction)
        BRGE   Jinc
Swap:   STOREF [array+B], D
        STOREF [array+B+1], C
Jinc:   ADDI   B, 1                 ; j++
        JUMP   Inner
Iinc:   ADDI   A, 1                 ; i++
        JUMP   Outer
End:    NOOP                        ; Do nothing

; Register allocation:
; A: i
; B: j
; C: array[j]
; D: last, array[j+1]

; Notes: i and j are optimized away. They exist only in registers, not in the main memory.
```

Assembly Version

```
.data
array   BYTE 7, 3, 2, 1, 6, 4, 5, 8
last    BYTE 7
temp    BYTE ?

.code
        LOADI  A, 0                 ; i = 0;
Outer:  LOAD   D, [last]            ; Load last into D
        LOADI  B, 0                 ; j = 0;
        CMP    A, D                 ; i < last
        BRGE   End                  ; If i >= last break out of the outer loop
Inner:  LOAD   D, [last]            ; Re-Load last into D (this register is shared)
        SUB    D, A                 ; D = D - A  (i.e., D = last - i)
        CMP    B, D                 ; j < last - i
        BRGE   Iinc                 ; If j >= last-i  branch to Iinc
If:     LOADF  C, [array+B]         ; C = array[j]
        LOADF  D, [array+B+1]       ; D = array[j+1] (compiler adds 1 to addr. of array)
        CMP    D, C                 ; if array[j+1] < array[j]  (switched direction)
        BRGE   Jinc
Swap:   STOREF [array+B], D
        STOREF [array+B+1], C
Jinc:   ADDI   B, 1                 ; j++
        JUMP   Inner
Iinc:   ADDI   A, 1                 ; i++
        JUMP   Outer
End:    NOOP                        ; Do nothing

; Register allocation:
; A: i
; B: j
; C: array[j]
; D: last, array[j+1]

; Notes: i and j are optimized away. They exist only in registers, not in the main memory.
```

Bubble Sort

```
int array[] = {7, 3, 2, 1, 6, 4, 5, 8};
int last = 7; // last valid index
int temp;
int i, j;



int main()
{
  for (i = 0; i < last; i++)
    for (j = 0; j < last-i; j++)
      if (array[j] > array[j+1]){
           temp = array[j];
           array[j] = array[j+1];
           array[j+1] = temp;
      }
   //for(i = 0; i < N; i++){
   //    printf("%d, ", array[i]);
   //}
}
```

```
.data
array   BYTE 7, 3, 2, 1, 6, 4, 5, 8
last    BYTE 7
temp    BYTE ?

.code
        LOADI  A, 0            ; i = 0;
Outer:  LOAD   D, [last]       ; Load last into D
        LOADI  B, 0            ; j = 0;
        CMP    A, D            ; i < last
        BRGE   End             ; If i >= last
Inner:  LOAD   D, [last]       ; Re-Load last into D
        SUB    D, A            ; D=D-A, i.e., D=last-i
        CMP    B, D            ; j < last - i
        BRGE   Iinc            ; If j >= last-i
If:     LOADF  C, [array+B]    ; C = array[j]
        LOADF  D, [array+B+1]  ; D = array[j+1]
        CMP    D, C            ; array[j+1] < array[j]
        BRGE   Jinc
Swap:   STOREF [array+B], D
        STOREF [array+B+1], C
Jinc:   ADDI   B, 1            ; j++
        JUMP   Inner
Iinc:   ADDI   A, 1            ; i++
        JUMP   Outer
End:    NOOP
; Register allocation:
; A: i
; B: j
; C: array[j]
; D: last, array[j+1]  (shared)

; Notes: i and j are optimized away to registers.
```

Machine Code Version

```
.data
array   BYTE 7, 3, 2, 1, 6, 4, 5, 8
last    BYTE 7
temp    BYTE ?

.code
        LOADI  A, 0
Outer:  LOAD   D, [last]
        LOADI  B, 0
        CMP    A, D
        BRGE   End
Inner:  LOAD   D, [last]
        SUB    D, A
        CMP    B, D
        BRGE   Iinc
If:     LOADF  C, [array+B]
        LOADF  D, [array+B+1]
        CMP    D, C
        BRGE   Jinc
Swap:   STOREF [array+B], D
        STOREF [array+B+1], C
Jinc:   ADDI   B, 1
        JUMP   Inner
Iinc:   ADDI   A, 1
        JUMP   Outer
End:    NOOP
```

Machine Code Version

```
.data
array   BYTE 7, 3, 2, 1, 6, 4, 5, 8
last    BYTE 7
temp    BYTE ?

.code
        LOADI  A, 0
Outer:  LOAD   D, [last]
        LOADI  B, 0
        CMP    A, D
        BRGE   End
Inner:  LOAD   D, [last]
        SUB    D, A
        CMP    B, D
        BRGE   Iinc
If:     LOADF  C, [array+B]
        LOADF  D, [array+B+1]
        CMP    D, C
        BRGE   Jinc
Swap:   STOREF [array+B], D
        STOREF [array+B+1], C
Jinc:   ADDI   B, 1
        JUMP   Inner
Iinc:   ADDI   A, 1
        JUMP   Outer
End:    NOOP
```

Data Memory:

```
00000111
00000011
00000010
00000001
00000110
00000100
00000101
00001000
00000111
00000000
```

Machine Code Version

```
.data
array   BYTE 7, 3, 2, 1, 6, 4, 5, 8
last    BYTE 7
temp    BYTE ?

.code
        LOADI  A, 0
Outer:  LOAD   D, [last]
        LOADI  B, 0
        CMP    A, D
        BRGE   End
Inner:  LOAD   D, [last]
        SUB    D, A
        CMP    B, D
        BRGE   Iinc
If:     LOADF  C, [array+B]
        LOADF  D, [array+B+1]
        CMP    D, C
        BRGE   Jinc
Swap:   STOREF [array+B], D
        STOREF [array+B+1], C
Jinc:   ADDI   B, 1
        JUMP   Inner
Iinc:   ADDI   A, 1
        JUMP   Outer
End:    NOOP
```

Data Memory:

```
00000111 //array[0]
00000011 //array[1]
00000010 //array[2]
00000001 //array[3]
00000110 //array[4]
00000100 //array[5]
00000101 //array[6]
00001000 //array[7]
00000111 //last
00000000 //temp
```

Machine Code Version

```
.data
array   BYTE 7, 3, 2, 1, 6, 4, 5, 8
last    BYTE 7
temp    BYTE ?

.code
        LOADI  A, 0
Outer:  LOAD   D, [last]
        LOADI  B, 0
        CMP    A, D
        BRGE   End
Inner:  LOAD   D, [last]
        SUB    D, A
        CMP    B, D
        BRGE   Iinc
If:     LOADF  C, [array+B]
        LOADF  D, [array+B+1]
        CMP    D, C
        BRGE   Jinc
Swap:   STOREF [array+B], D
        STOREF [array+B+1], C
Jinc:   ADDI   B, 1
        JUMP   Inner
Iinc:   ADDI   A, 1
        JUMP   Outer
End:    NOOP
```

Address	Data Memory:
0000	00000111 //array[0]
0001	00000011 //array[1]
0010	00000010 //array[2]
0011	00000001 //array[3]
0100	00000110 //array[4]
0101	00000100 //array[5]
0110	00000101 //array[6]
0111	00001000 //array[7]
1000	00000111 //last
1001	00000000 //temp

Machine Code Version

```
.data
array   BYTE 7, 3, 2, 1, 6, 4, 5, 8
last    BYTE 7
temp    BYTE ?

.code
        LOADI  A, 0
Outer:  LOAD   D, [last]
        LOADI  B, 0
        CMP    A, D
        BRGE   End
Inner:  LOAD   D, [last]
        SUB    D, A
        CMP    B, D
        BRGE   Iinc
If:     LOADF  C, [array+B]
        LOADF  D, [array+B+1]
        CMP    D, C
        BRGE   Jinc
Swap:   STOREF [array+B], D
        STOREF [array+B+1], C
Jinc:   ADDI   B, 1
        JUMP   Inner
Iinc:   ADDI   A, 1
        JUMP   Outer
End:    NOOP
```

Address	Data Memory:
0000	00000111 //array[0]
0001	00000011 //array[1]
0010	00000010 //array[2]
0011	00000001 //array[3]
0100	00000110 //array[4]
0101	00000100 //array[5]
0110	00000101 //array[6]
0111	00001000 //array[7]
1000	00000111 //last
1001	00000000 //temp
1010	00000000
1011	00000000
1100	00000000
1101	00000000
1110	00000000
1111	00000000

Machine Code Version

```
.data
array   BYTE 7, 3, 2, 1, 6, 4, 5, 8
last    BYTE 7
temp    BYTE ?

.code
        LOADI  A, 0
Outer:  LOAD   D, [last]
        LOADI  B, 0
        CMP    A, D
        BRGE   End
Inner:  LOAD   D, [last]
        SUB    D, A
        CMP    B, D
        BRGE   Iinc
If:     LOADF  C, [array+B]
        LOADF  D, [array+B+1]
        CMP    D, C
        BRGE   Jinc
Swap:   STOREF [array+B], D
        STOREF [array+B+1], C
Jinc:   ADDI   B, 1
        JUMP   Inner
Iinc:   ADDI   A, 1
        JUMP   Outer
End:    NOOP
```

Machine Code Version

```
.data
array   BYTE 7, 3, 2, 1, 6, 4, 5, 8
last    BYTE 7
temp    BYTE ?

.code
        LOADI  A, 0
Outer:  LOAD   D, [last]
        LOADI  B, 0
        CMP    A, D
        BRGE   End
Inner:  LOAD   D, [last]
        SUB    D, A
        CMP    B, D
        BRGE   Iinc
If:     LOADF  C, [array+B]
        LOADF  D, [array+B+1]
        CMP    D, C
        BRGE   Jinc
Swap:   STOREF [array+B], D
        STOREF [array+B+1], C
Jinc:   ADDI   B, 1
        JUMP   Inner
Iinc:   ADDI   A, 1
        JUMP   Outer
End:    NOOP
```

Code Memory:

```
0011000000000000
1000110000001000
0011010000000000
1101001100000000
1111001100001110
1000110000001000
0110110000000000
1101011100000000
1111001100001000
1001100100000000
1001110100000001
1101111000000000
1111001100000010
1011110100000000
1011100100000001
0101010000000001
1110000011110100
0101000000000001
1110000011101110
0000000000000000
```

Machine Code Version

```
.data
array   BYTE 7, 3, 2, 1, 6, 4, 5, 8
last    BYTE 7
temp    BYTE ?

.code
        LOADI  A, 0
Outer:  LOAD   D, [last]
        LOADI  B, 0
        CMP    A, D
        BRGE   End
Inner:  LOAD   D, [last]
        SUB    D, A
        CMP    B, D
        BRGE   Iinc
If:     LOADF  C, [array+B]
        LOADF  D, [array+B+1]
        CMP    D, C
        BRGE   Jinc
Swap:   STOREF [array+B], D
        STOREF [array+B+1], C
Jinc:   ADDI   B, 1
        JUMP   Inner
Iinc:   ADDI   A, 1
        JUMP   Outer
End:    NOOP
```

Address	Code Memory:
100000	0011000000000000
100001	1000110000001000
100010	0011010000000000
100011	1101001100000000
100100	1111001100001110
100101	1000110000001000
100110	0110110000000000
100111	1101011100000000
101000	1111001100001000
101001	1001100100000000
101010	1001110100000001
101011	1101111000000000
101100	1111001100000010
101101	1011110100000000
101110	1011100100000001
101111	0101010000000001
110000	1110000011110100
110001	0101000000000001
110010	1110000011101110
110011	0000000000000000

Machine Code Version

```
.data
array   BYTE 7, 3, 2, 1, 6, 4, 5, 8
last    BYTE 7
temp    BYTE ?

.code
        LOADI  A, 0
Outer:  LOAD   D, [last]
        LOADI  B, 0
        CMP    A, D
        BRGE   End
Inner:  LOAD   D, [last]
        SUB    D, A
        CMP    B, D
        BRGE   Iinc
If:     LOADF  C, [array+B]
        LOADF  D, [array+B+1]
        CMP    D, C
        BRGE   Jinc
Swap:   STOREF [array+B], D
        STOREF [array+B+1], C
Jinc:   ADDI   B, 1
        JUMP   Inner
Iinc:   ADDI   A, 1
        JUMP   Outer
End:    NOOP
```

Address	Code Memory:
100000	0011000000000000
100001	1000110000001000
100010	0011010000000000
100011	1101001100000000
100100	1111001100001110
100101	1000110000001000
100110	0110110000000000
100111	1101011100000000
101000	1111001100001000
101001	1001100100000000
101010	1001110100000001
101011	1101111000000000
101100	1111001100000010
101101	1011110100000000
101110	1011100100000001
101111	0101010000000001
110000	1110000011110100
110001	0101000000000001
110010	1110000011101110
110011	0000000000000000
110100	0000000000000000
. . .	. . .
111110	0000000000000000
111111	0000000000000000

Assembly v.s. Machine Code

```
.code
        LOADI   A, 0
Outer:  LOAD    D, [last]
        LOADI   B, 0
        CMP     A, D
        BRGE    End
Inner:  LOAD    D, [last]
        SUB     D, A
        CMP     B, D
        BRGE    Iinc
If:     LOADF   C, [array+B]
        LOADF   D, [array+B+1]
        CMP     D, C
        BRGE    Jinc
Swap:   STOREF  [array+B], D
        STOREF  [array+B+1], C
Jinc:   ADDI    B, 1
        JUMP    Inner
Iinc:   ADDI    A, 1
        JUMP    Outer
End:    NOOP
```

```
Code Memory:
0011000000000000
1000110000001000
0011010000000000
1101001100000000
1111001100001110
1000110000001000
0110110000000000
1101011100000000
1111001100001000
1001100100000000
1001110100000001
1101111000000000
1111001100000010
1011110100000000
1011100100000001
0101010000000001
1110000011110100
0101000000000001
1110000011101110
0000000000000000
```

Assembly v.s. Machine Code

```
.code
        LOADI   A, 0
Outer:  LOAD    D, [last]
        LOADI   B, 0
        CMP     A, D
        BRGE    End
Inner:  LOAD    D, [last]
        SUB     D, A
        CMP     B, D
        BRGE    Iinc
If:     LOADF   C, [array+B]
        LOADF   D, [array+B+1]
        CMP     D, C
        BRGE    Jinc
Swap:   STOREF  [array+B], D
        STOREF  [array+B+1], C
Jinc:   ADDI    B, 1
        JUMP    Inner
Iinc:   ADDI    A, 1
        JUMP    Outer
End:    NOOP
```

```
Code Memory:
00110000_00000000
10001100_00001000
00110100_00000000
11010011_00000000
11110011_00001110
10001100_00001000
01101100_00000000
11010111_00000000
11110011_00001000
10011001_00000000
10011101_00000001
11011110_00000000
11110011_00000010
10111101_00000000
10111001_00000001
01010100_00000001
11100000_11110100
01010000_00000001
11100000_11101110
00000000_00000000
```

Assembly v.s. Machine Code

```
.code
        LOADI   A, 0
Outer:  LOAD    D, [last]
        LOADI   B, 0
        CMP     A, D
        BRGE    End
Inner:  LOAD    D, [last]
        SUB     D, A
        CMP     B, D
        BRGE    Iinc
If:     LOADF   C, [array+B]
        LOADF   D, [array+B+1]
        CMP     D, C
        BRGE    Jinc
Swap:   STOREF  [array+B], D
        STOREF  [array+B+1], C
Jinc:   ADDI    B, 1
        JUMP    Inner
Iinc:   ADDI    A, 1
        JUMP    Outer
End:    NOOP
```

```
Code Memory:
0011_00_00_00000000
1000_11_00_00001000
0011_01_00_00000000
1101_00_11_00000000
1111_00_11_00001110
1000_11_00_00001000
0110_11_00_00000000
1101_01_11_00000000
1111_00_11_00001000
1001_10_01_00000000
1001_11_01_00000001
1101_11_10_00000000
1111_00_11_00000010
1011_11_01_00000000
1011_10_01_00000001
0101_01_00_00000001
1110_00_00_11110100
0101_00_00_00000001
1110_00_00_11101110
0000_00_00_00000000
```

Assembly v.s. Machine Code

```
.code
        LOADI   A, 0
Outer:  LOAD    D, [last]
        LOADI   B, 0
        CMP     A, D
        BRGE    End
Inner:  LOAD    D, [last]
        SUB     D, A
        CMP     B, D
        BRGE    Iinc
If:     LOADF   C, [array+B]
        LOADF   D, [array+B+1]
        CMP     D, C
        BRGE    Jinc
Swap:   STOREF  [array+B], D
        STOREF  [array+B+1], C
Jinc:   ADDI    B, 1
        JUMP    Inner
Iinc:   ADDI    A, 1
        JUMP    Outer
End:    NOOP
```

```
Code Memory:
0011_00_00_00000000
1000_11_00_00001000
0011_01_00_00000000
1101_00_11_00000000
1111_00_11_00001110
1000_11_00_00001000
0110_11_00_00000000
1101_01_11_00000000
1111_00_11_00001000
1001_10_01_00000000
1001_11_01_00000001
1101_11_10_00000000
1111_00_11_00000010
1011_11_01_00000000
1011_10_01_00000001
0101_01_00_00000001
1110_00_00_11110100
0101_00_00_00000001
1110_00_00_11101110
0000_00_00_00000000
```

Assembly v.s. Machine Code

```
.code
        LOADI   A, 0
Outer:  LOAD    D, [last]
        LOADI   B, 0
        CMP     A, D
        BRGE    End
Inner:  LOAD    D, [last]
        SUB     D, A
        CMP     B, D
        BRGE    Iinc
If:     LOADF   C, [array+B]
        LOADF   D, [array+B+1]
        CMP     D, C
        BRGE    Jinc
Swap:   STOREF  [array+B], D
        STOREF  [array+B+1], C
Jinc:   ADDI    B, 1
        JUMP    Inner
Iinc:   ADDI    A, 1
        JUMP    Outer
End:    NOOP
```

```
Code Memory:
0011_00_00_00000000
1000_11_00_00001000
0011_01_00_00000000
1101_00_11_00000000
1111_00_11_00001110
1000_11_00_00001000
0110_11_00_00000000
1101_01_11_00000000
1111_00_11_00001000
1001_10_01_00000000
1001_11_01_00000001
1101_11_10_00000000
1111_00_11_00000010
1011_11_01_00000000
1011_10_01_00000001
0101_01_00_00000001
1110_00_00_11110100
0101_00_00_00000001
1110_00_00_11101110
0000_00_00_00000000
```

Assembly v.s. Machine Code

```
.code
        LOADI   A, 0
Outer:  LOAD    D, [last]
        LOADI   B, 0
        CMP     A, D
        BRGE    End
Inner:  LOAD    D, [last]
        SUB     D, A
        CMP     B, D
        BRGE    Iinc
If:     LOADF   C, [array+B]
        LOADF   D, [array+B+1]
        CMP     D, C
        BRGE    Jinc
Swap:   STOREF  [array+B], D
        STOREF  [array+B+1], C
Jinc:   ADDI    B, 1
        JUMP    Inner
Iinc:   ADDI    A, 1
        JUMP    Outer
End:    NOOP
```

```
Code Memory:
0011_00_00_00000000
1000_11_00_00001000
0011_01_00_00000000
1101_00_11_00000000
1111_00_11_00001110
1000_11_00_00001000
0110_11_00_00000000
1101_01_11_00000000
1111_00_11_00001000
1001_10_01_00000000
1001_11_01_00000001
1101_11_10_00000000
1111_00_11_00000010
1011_11_01_00000000
1011_10_01_00000001
0101_01_00_00000001
1110_00_00_11110100
0101_00_00_00000001
1110_00_00_11101110
0000_00_00_00000000
```

Assembly v.s. Machine Code

```
.code
        LOADI   A, 0
Outer:  LOAD    D, [last]
        LOADI   B, 0
        CMP     A, D
        BRGE    End
Inner:  LOAD    D, [last]
        SUB     D, A
        CMP     B, D
        BRGE    Iinc
If:     LOADF   C, [array+B]
        LOADF   D, [array+B+1]
        CMP     D, C
        BRGE    Jinc
Swap:   STOREF  [array+B], D
        STOREF  [array+B+1], C
Jinc:   ADDI    B, 1
        JUMP    Inner
Iinc:   ADDI    A, 1
        JUMP    Outer
End:    NOOP
```

```
Code Memory:
0011_00_00_00000000
1000_11_00_00001000
0011_01_00_00000000
1101_00_11_00000000
1111_00_11_00001110
1000_11_00_00001000
0110_11_00_00000000
1101_01_11_00000000
1111_00_11_00001000
1001_10_01_00000000
1001_11_01_00000001
1101_11_10_00000000
1111_00_11_00000010
1011_11_01_00000000
1011_10_01_00000001
0101_01_00_00000001
1110_00_00_11110100
0101_00_00_00000001
1110_00_00_11101110
0000_00_00_00000000
```

Assembly v.s. Machine Code

```
.code
        LOADI   A, 0
Outer:  LOAD    D, [last]
        LOADI   B, 0
        CMP     A, D
        BRGE    End
Inner:  LOAD    D, [last]
        SUB     D, A
        CMP     B, D
        BRGE    Iinc
If:     LOADF   C, [array+B]
        LOADF   D, [array+B+1]
        CMP     D, C
        BRGE    Jinc
Swap:   STOREF  [array+B], D
        STOREF  [array+B+1], C
Jinc:   ADDI    B, 1
        JUMP    Inner
Iinc:   ADDI    A, 1
        JUMP    Outer
End:    NOOP
```

```
Code Memory:
0011_00_00_00000000
1000_11_00_00001000
0011_01_00_00000000
1101_00_11_00000000
1111_00_11_00001110
1000_11_00_00001000
0110_11_00_00000000
1101_01_11_00000000
1111_00_11_00001000
1001_10_01_00000000
1001_11_01_00000001
1101_11_10_00000000
1111_00_11_00000010
1011_11_01_00000000
1011_10_01_00000001
0101_01_00_00000001
1110_00_00_11110100
0101_00_00_00000001
1110_00_00_11101110
0000_00_00_00000000
```

Assembly v.s. Machine Code

```
.code
        LOADI   A, 0
Outer:  LOAD    D, [last]
        LOADI   B, 0
        CMP     A, D
        BRGE    End
Inner:  LOAD    D, [last]
        SUB     D, A
        CMP     B, D
        BRGE    Iinc
If:     LOADF   C, [array+B]
        LOADF   D, [array+B+1]
        CMP     D, C
        BRGE    Jinc
Swap:   STOREF  [array+B], D
        STOREF  [array+B+1], C
Jinc:   ADDI    B, 1
        JUMP    Inner
Iinc:   ADDI    A, 1
        JUMP    Outer
End:    NOOP
```

```
Code Memory:
0011_00_00_00000000
1000_11_00_00001000
0011_01_00_00000000
1101_00_11_00000000
1111_00_11_00001110
1000_11_00_00001000
0110_11_00_00000000
1101_01_11_00000000
1111_00_11_00001000
1001_10_01_00000000
1001_11_01_00000001
1101_11_10_00000000
1111_00_11_00000010
1011_11_01_00000000
1011_10_01_00000001
0101_01_00_00000001
1110_00_00_11110100
0101_00_00_00000001
1110_00_00_11101110
0000_00_00_00000000
```

Assembly v.s. Machine Code

```
.code
        LOADI   A, 0
Outer:  LOAD    D, [last]
        LOADI   B, 0
        CMP     A, D
        BRGE    End
Inner:  LOAD    D, [last]
        SUB     D, A
        CMP     B, D
        BRGE    Iinc
If:     LOADF   C, [array+B]
        LOADF   D, [array+B+1]
        CMP     D, C
        BRGE    Jinc
Swap:   STOREF  [array+B], D
        STOREF  [array+B+1], C
Jinc:   ADDI    B, 1
        JUMP    Inner
Iinc:   ADDI    A, 1
        JUMP    Outer
End:    NOOP
```

```
Code Memory:
0011_00_00_00000000
1000_11_00_00001000
0011_01_00_00000000
1101_00_11_00000000
1111_00_11_00001110
1000_11_00_00001000
0110_11_00_00000000
1101_01_11_00000000
1111_00_11_00001000
1001_10_01_00000000
1001_11_01_00000001
1101_11_10_00000000
1111_00_11_00000010
1011_11_01_00000000
1011_10_01_00000001
0101_01_00_00000001
1110_00_00_11110100
0101_00_00_00000001
1110_00_00_11101110
0000_00_00_00000000
```

Assembly v.s. Machine Code

```
.code
        LOADI   A, 0
Outer:  LOAD    D, [last]
        LOADI   B, 0
        CMP     A, D
        BRGE    End
Inner:  LOAD    D, [last]
        SUB     D, A
        CMP     B, D
        BRGE    Iinc
If:     LOADF   C, [array+B]
        LOADF   D, [array+B+1]
        CMP     D, C
        BRGE    Jinc
Swap:   STOREF  [array+B], D
        STOREF  [array+B+1], C
Jinc:   ADDI    B, 1
        JUMP    Inner
Iinc:   ADDI    A, 1
        JUMP    Outer
End:    NOOP
```

```
Code Memory:
0011_00_00_00000000
1000_11_00_00001000
0011_01_00_00000000
1101_00_11_00000000
1111_00_11_00001110
1000_11_00_00001000
0110_11_00_00000000
1101_01_11_00000000
1111_00_11_00001000
1001_10_01_00000000
1001_11_01_00000001
1101_11_10_00000000
1111_00_11_00000010
1011_11_01_00000000
1011_10_01_00000001
0101_01_00_00000001
1110_00_00_11110100
0101_00_00_00000001
1110_00_00_11101110
0000_00_00_00000000
```

Assembly v.s. Machine Code

```
.code
        LOADI   A, 0
Outer:  LOAD    D, [last]
        LOADI   B, 0
        CMP     A, D
        BRGE    End
Inner:  LOAD    D, [last]
        SUB     D, A
        CMP     B, D
        BRGE    Iinc
If:     LOADF   C, [array+B]
        LOADF   D, [array+B+1]
        CMP     D, C
        BRGE    Jinc
Swap:   STOREF  [array+B], D
        STOREF  [array+B+1], C
Jinc:   ADDI    B, 1
        JUMP    Inner
Iinc:   ADDI    A, 1
        JUMP    Outer
End:    NOOP
```

```
Code Memory:
0011_00_dd_00000000
1000_11_dd_00001000
0011_01_dd_00000000
1101_00_11_dddddddd
1111_dd_11_00001110
1000_11_dd_00001000
0110_11_00_dddddddd
1101_01_11_dddddddd
1111_dd_11_00001000
1001_10_01_00000000
1001_11_01_00000001
1101_11_10_dddddddd
1111_dd_11_00000010
1011_11_01_00000000
1011_10_01_00000001
0101_01_dd_00000001
1110_dd_dd_11110100
0101_00_dd_00000001
1110_dd_dd_11101110
0000_dd_dd_dddddddd
```

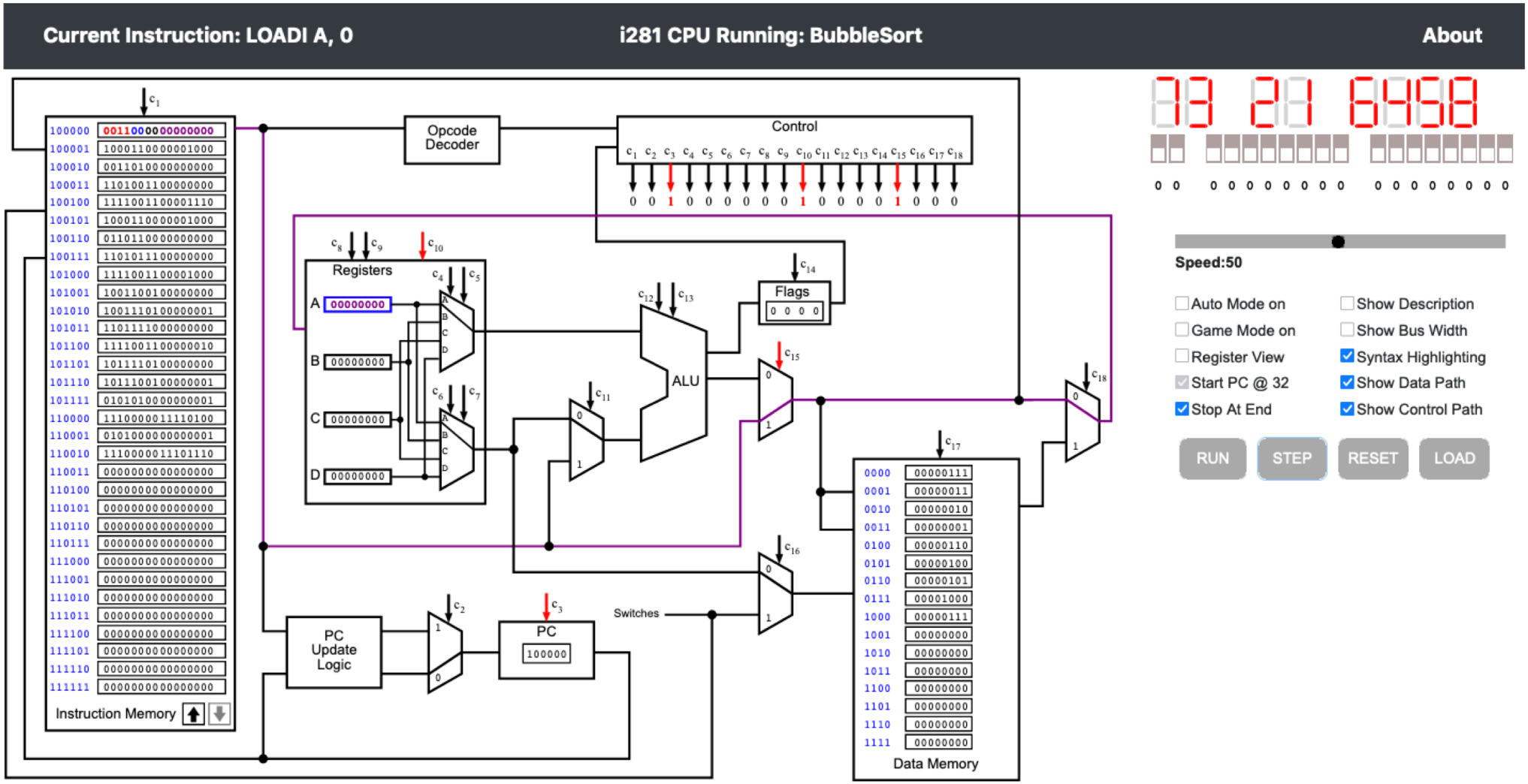
Assembly v.s. Machine Code

```
.code
        LOADI   A, 0
Outer:  LOAD    D, [last]
        LOADI   B, 0
        CMP     A, D
        BRGE    End
Inner:  LOAD    D, [last]
        SUB     D, A
        CMP     B, D
        BRGE    Iinc
If:     LOADF   C, [array+B]
        LOADF   D, [array+B+1]
        CMP     D, C
        BRGE    Jinc
Swap:   STOREF  [array+B], D
        STOREF  [array+B+1], C
Jinc:   ADDI    B, 1
        JUMP    Inner
Iinc:   ADDI    A, 1
        JUMP    Outer
End:    NOOP
```

```
Code Memory:
0011_00_00_00000000
1000_11_00_00001000
0011_01_00_00000000
1101_00_11_00000000
1111_00_11_00001110
1000_11_00_00001000
0110_11_00_00000000
1101_01_11_00000000
1111_00_11_00001000
1001_10_01_00000000
1001_11_01_00000001
1101_11_10_00000000
1111_00_11_00000010
1011_11_01_00000000
1011_10_01_00000001
0101_01_00_00000001
1110_00_00_11110100
0101_00_00_00000001
1110_00_00_11101110
0000_00_00_00000000
```

For more examples try the i281 simulator

i281 Simulator



To try the simulator, go to the class web page and follow the link.

Questions?

THE END