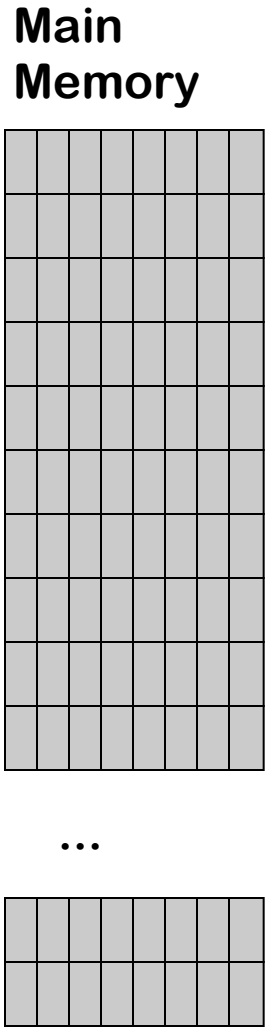
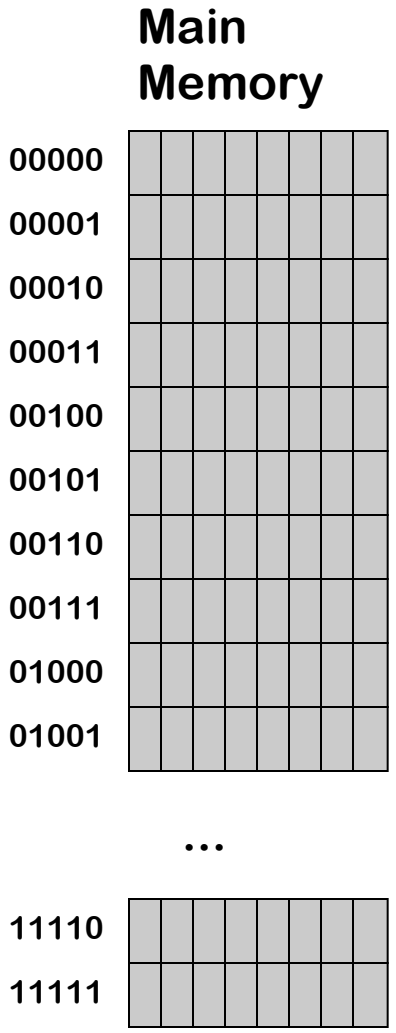
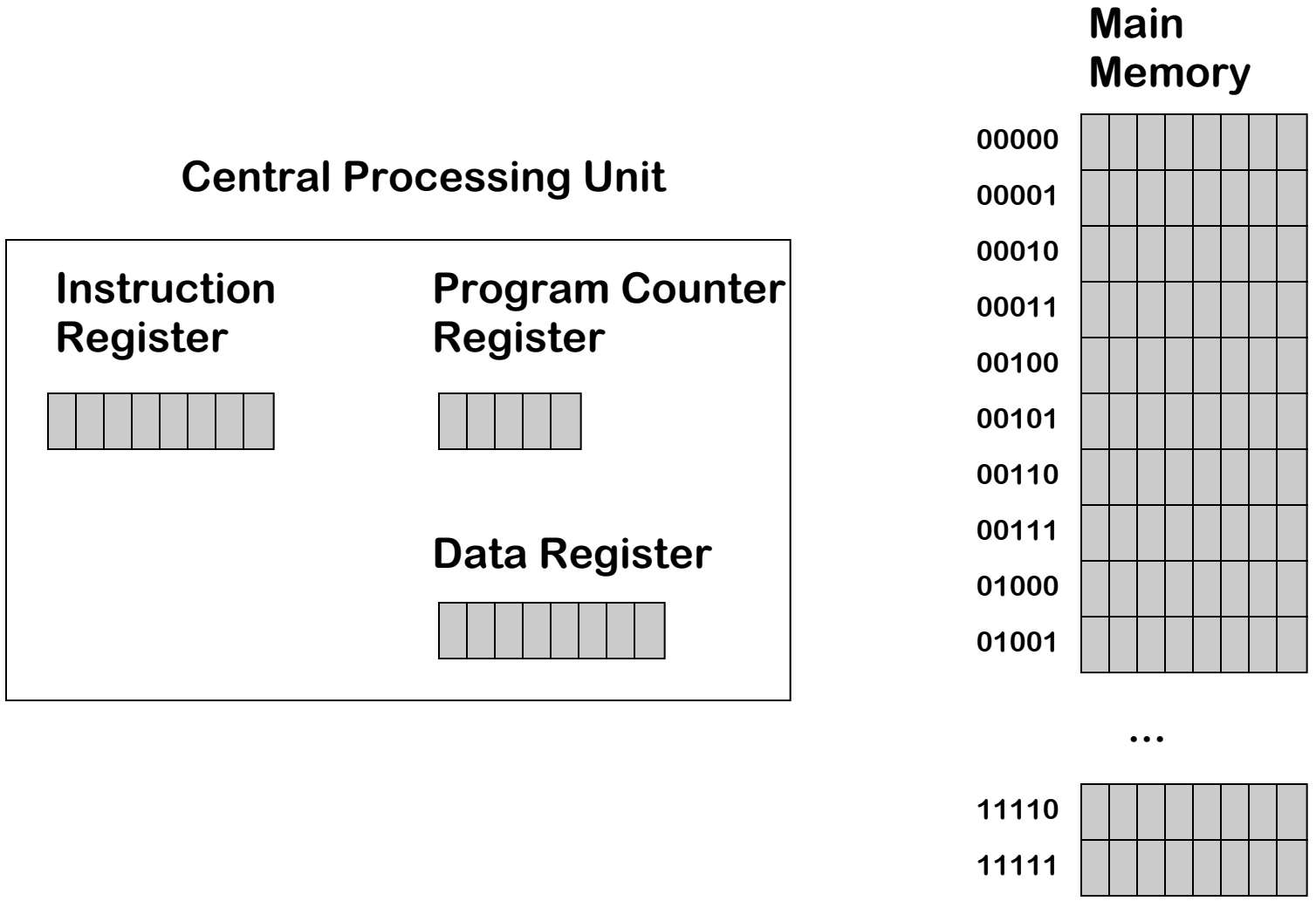
Our Example Architecture



Our Example Architecture



Our Example Architecture

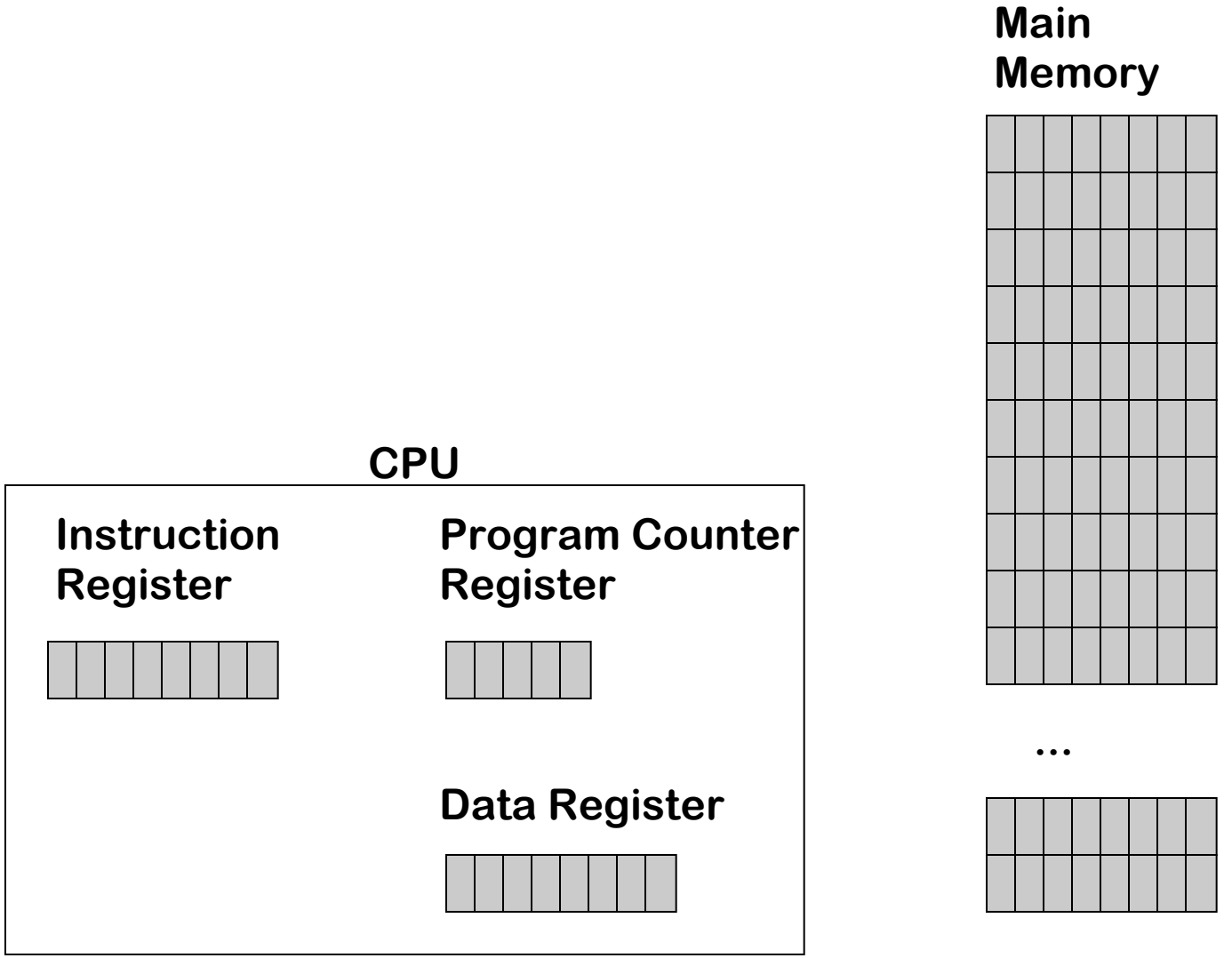


Woody's Machine Language

Assembly Language Instruction	Machine Language Instruction
CopyFrom	000
CopyTo	001
Add	010
Subtract	011
Read	100
Print	101
IfNegGoTo	110
Stop	111

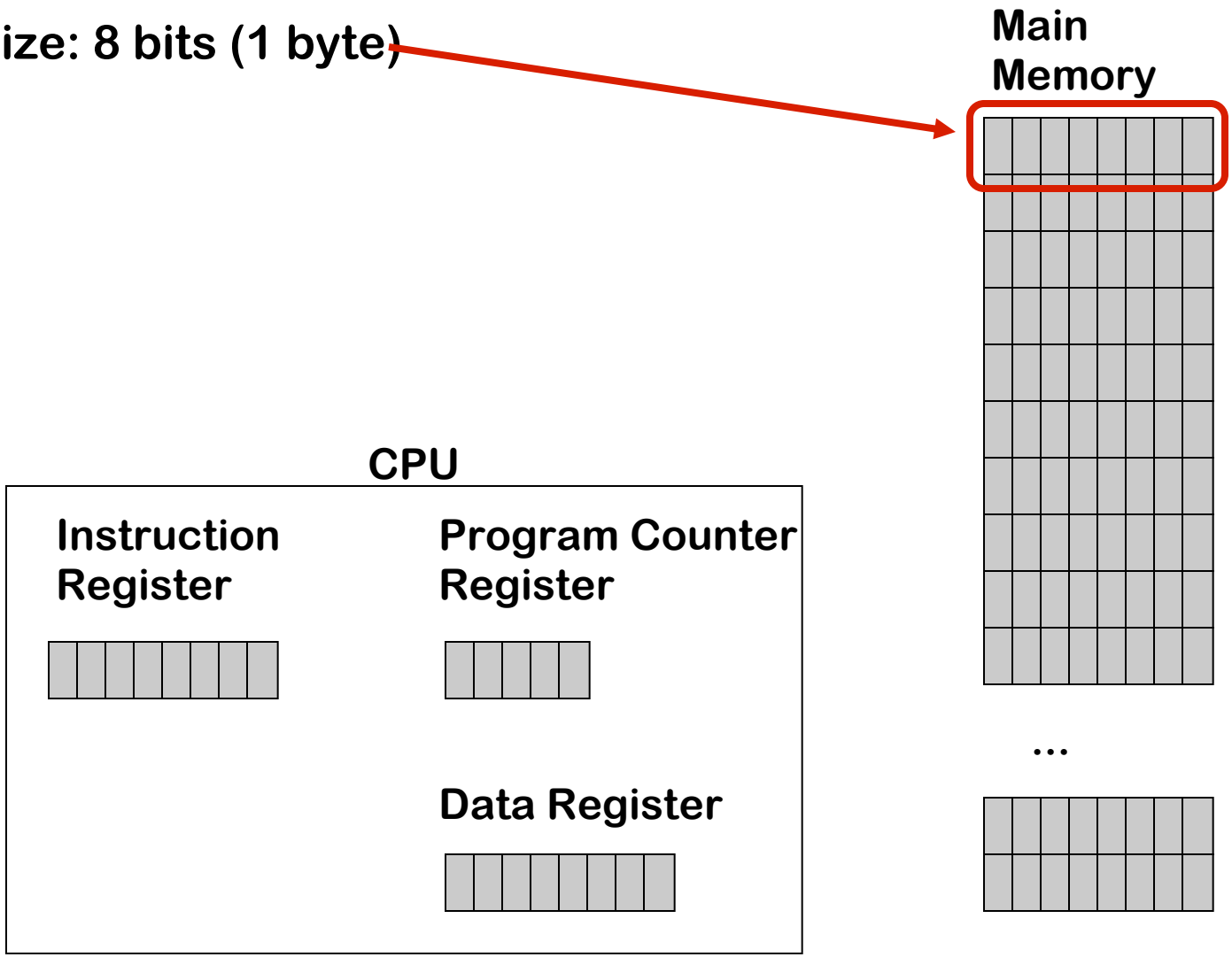
Program Execution

Our Hypothetical Computer



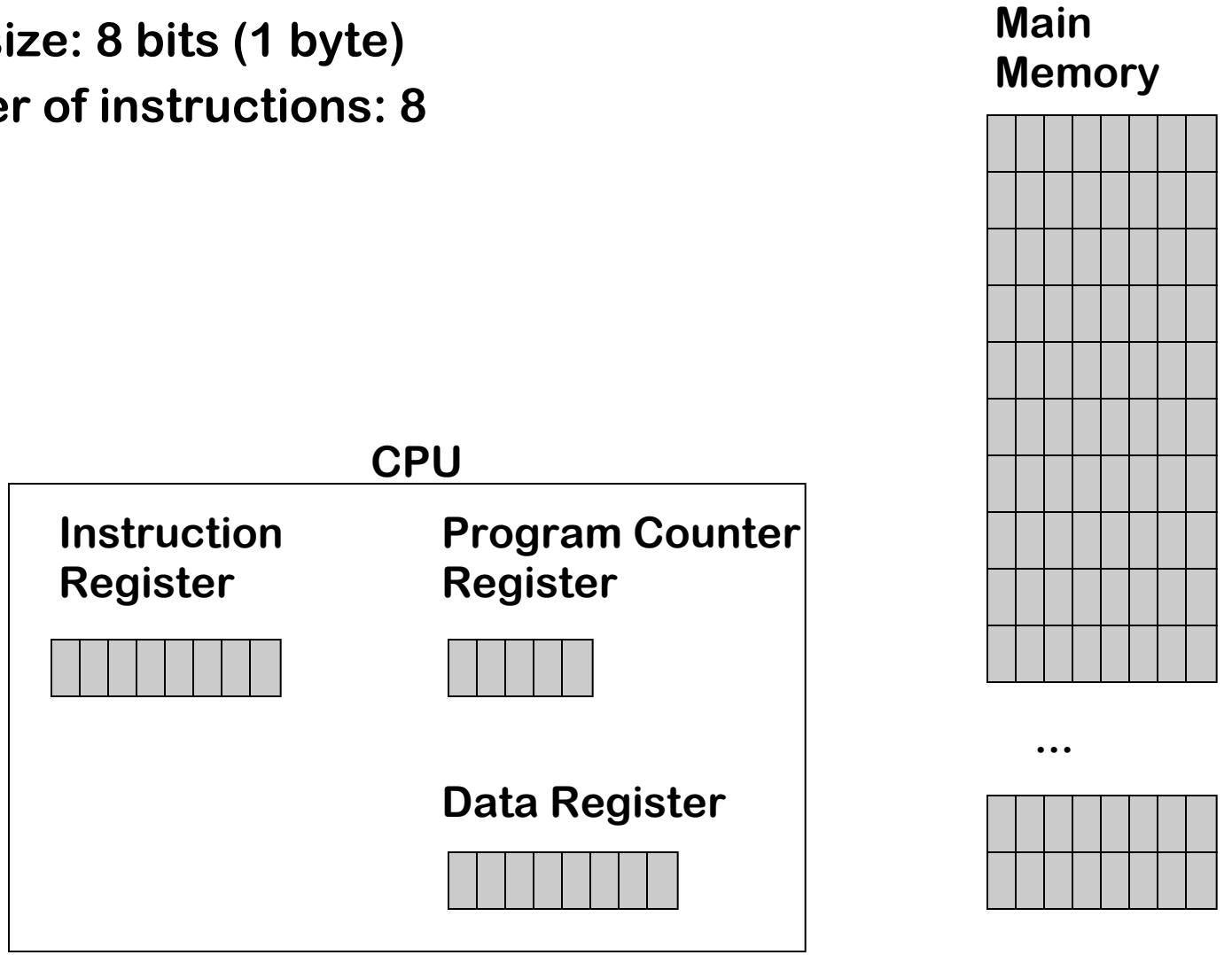
Our Hypothetical Computer

- Word size: 8 bits (1 byte)



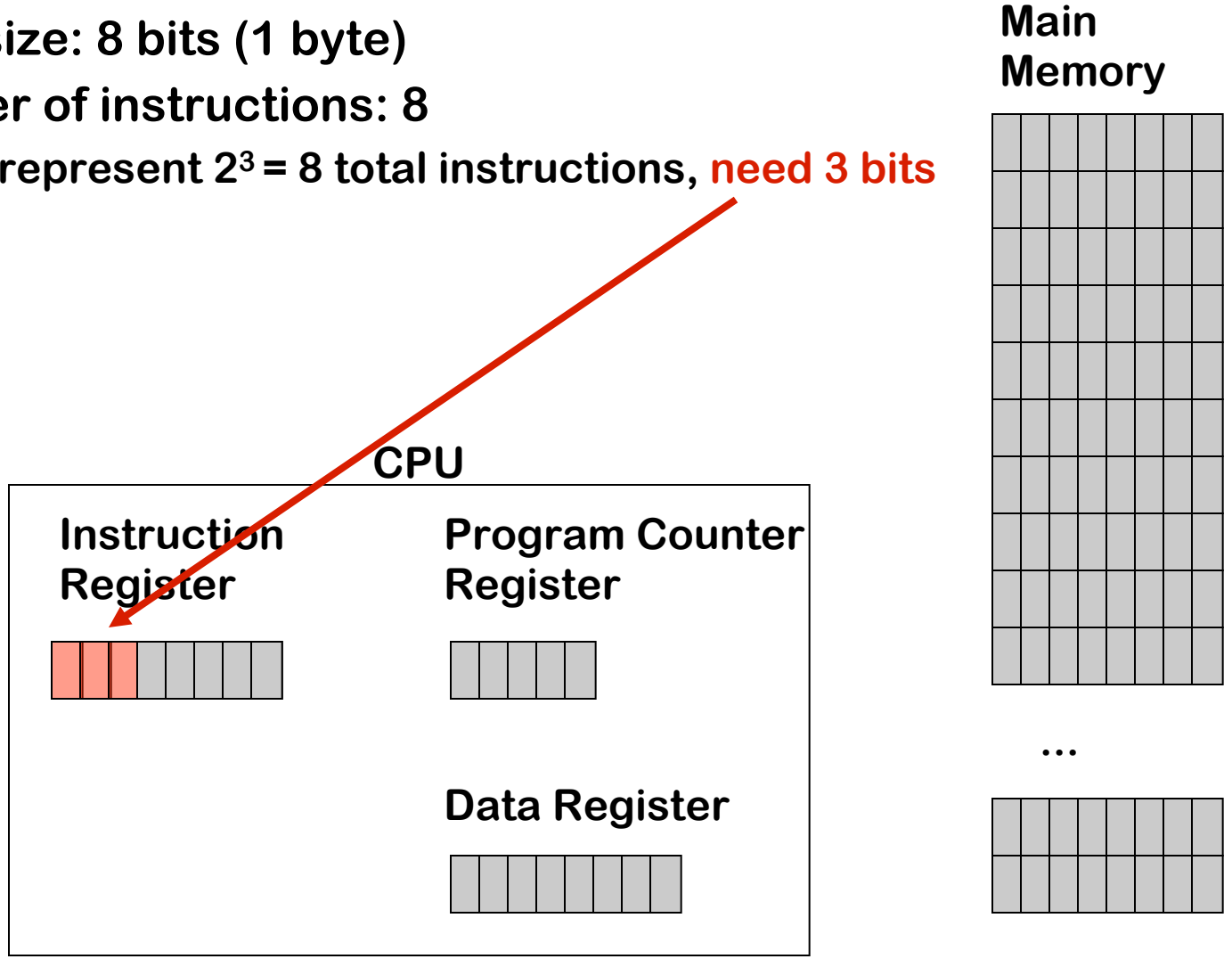
Our Hypothetical Computer

- Word size: 8 bits (1 byte)
- Number of instructions: 8



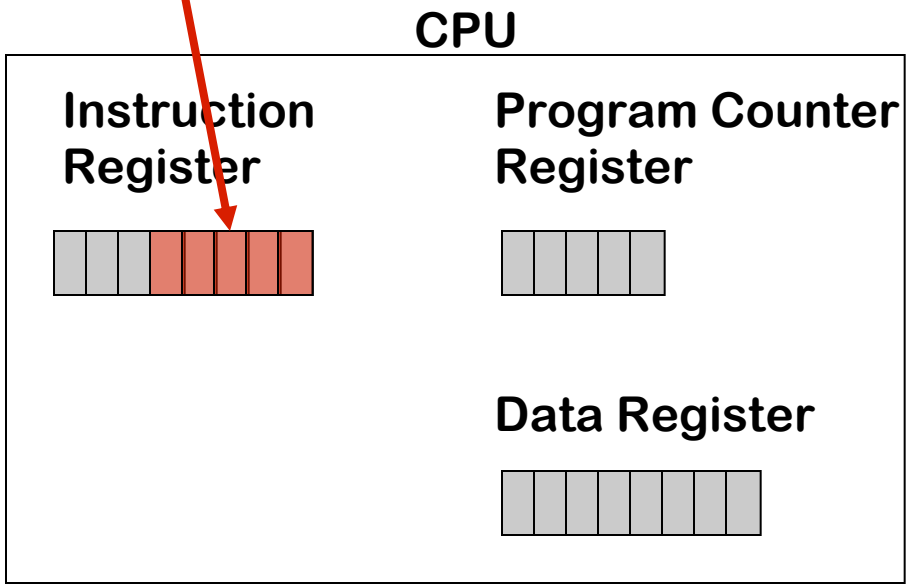
Our Hypothetical Computer

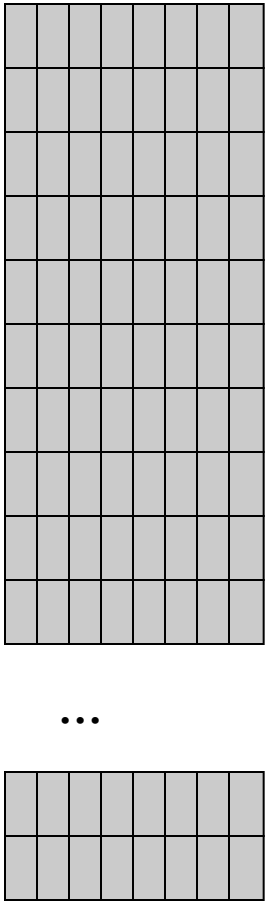
- Word size: 8 bits (1 byte)
- Number of instructions: 8
  - To represent $2^3 = 8$ total instructions, need 3 bits



Our Hypothetical Computer

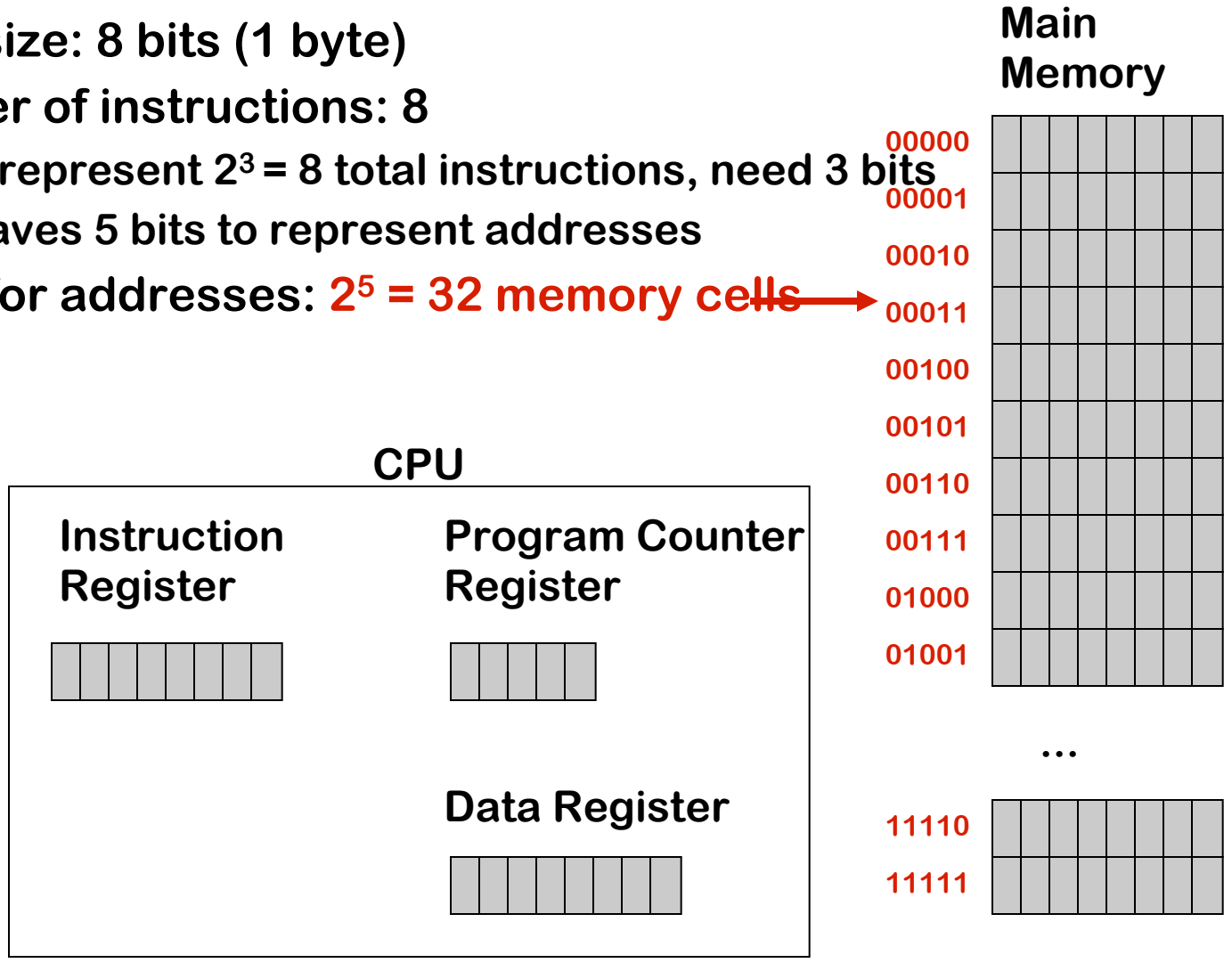
- Word size: 8 bits (1 byte)
- Number of instructions: 8
  - To represent $2^3 = 8$ total instructions, need 3 bits
  - Leaves 5 bits to represent addresses





Our Hypothetical Computer

- Word size: 8 bits (1 byte)
- Number of instructions: 8
  - To represent $2^3 = 8$ total instructions, need 3 bits
  - Leaves 5 bits to represent addresses
- 5 bits for addresses: $2^5 = 32$ memory cells



Eight Machine Language Instructions

Instruction Code	Meaning of the Instruction
000	Copy word from memory address into DR
001	Copy word to memory address from DR
010	Add word in memory address to word in DR
011	Subtract word in memory address from word in DR
100	Read word from input into DR
101	Print word in DR to output
110	Conditional execution : If word in DR is negative, copy a new memory address into PC
111	Stop execution

Underline: an argument (value) required by that instruction

Example of an Instruction

00110110

one word
(here, one byte)

Code	Meaning of the Instruction
000	Copy from address into DR
001	Copy to address from DR
010	Add word in address to DR
011	Subtract word in address from DR
100	Read from input into DR
101	Print to output from DR
110	If DR is < 0, copy address into PC
111	Stop execution

Example of an Instruction

00110110

Instruction code

Code	Meaning of the Instruction
000	Copy from address into DR
001	Copy to address from DR
010	Add word in address to DR
011	Subtract word in address from DR
100	Read from input into DR
101	Print to output from DR
110	If DR is < 0, copy address into PC
111	Stop execution

Example of an Instruction

001**10110**

Argument
(memory address)

Code	Meaning of the Instruction
000	Copy from address into DR
001	Copy to address from DR
010	Add word in address to DR
011	Subtract word in address from DR
100	Read from input into DR
101	Print to output from DR
110	If DR is < 0, copy address into PC
111	Stop execution

Example of an Instruction

00110110

Decoding the Instruction:

Code	Meaning of the Instruction
000	Copy from address into DR
001	Copy to address from DR
010	Add word in address to DR
011	Subtract word in address from DR
100	Read from input into DR
101	Print to output from DR
110	If DR is < 0, copy address into PC
111	Stop execution

Example of an Instruction

00110110

Decoding the Instruction:

Copy to …

Code	Meaning of the Instruction
000	Copy from address into DR
001	Copy to address from DR
010	Add word in address to DR
011	Subtract word in address from DR
100	Read from input into DR
101	Print to output from DR
110	If DR is < 0, copy address into PC
111	Stop execution

Example of an Instruction

00110110

Decoding the Instruction:

Copy to …

Code	Meaning of the Instruction
000	Copy from address into DR
001	Copy to address from DR
010	Add word in address to DR
011	Subtract word in address from DR
100	Read from input into DR
101	Print to output from DR
110	If DR is < 0, copy address into PC
111	Stop execution

Example of an Instruction

00110110

Decoding the Instruction:

Copy to address 10110…

Code	Meaning of the Instruction
000	Copy from address into DR
001	Copy to address from DR
010	Add word in address to DR
011	Subtract word in address from DR
100	Read from input into DR
101	Print to output from DR
110	If DR is < 0, copy address into PC
111	Stop execution

Example of an Instruction

00110110

Decoding the Instruction:

Copy to address 10110 from DR

This instruction copies the contents of the data register into memory cell addressed $10110_2 = 22_{10}$

Code	Meaning of the Instruction
000	Copy from address into DR
001	Copy to address from DR
010	Add word in address to DR
011	Subtract word in address from DR
100	Read from input into DR
101	Print to output from DR
110	If DR is < 0, copy address into PC
111	Stop execution

Example of an Instruction

10000000

Decoding the Instruction:

Read from input…

Code	Meaning of the Instruction
000	Copy from address into DR
001	Copy to address from DR
010	Add word in address to DR
011	Subtract word in address from DR
100	Read from input into DR
101	Print to output from DR
110	If DR is < 0, copy address into PC
111	Stop execution

Example of an Instruction

10000000

Decoding the Instruction:

Read from input…

No argument…

Code	Meaning of the Instruction
000	Copy from address into DR
001	Copy to address from DR
010	Add word in address to DR
011	Subtract word in address from DR
100	Read from input into DR
101	Print to output from DR
110	If DR is < 0, copy address into PC
111	Stop execution

Example of an Instruction

10000000

Decoding the Instruction:

Read from input…

No argument, hence zeros (to fill the byte)

Code	Meaning of the Instruction
000	Copy from address into DR
001	Copy to address from DR
010	Add word in address to DR
011	Subtract word in address from DR
100	Read from input into DR
101	Print to output from DR
110	If DR is < 0, copy address into PC
111	Stop execution

Example of an Instruction

10000000

Decoding the Instruction:

Read from input into DR

This instruction copies a word from the input unit into the data register

Code	Meaning of the Instruction
000	Copy from address into DR
001	Copy to address from DR
010	Add word in address to DR
011	Subtract word in address from DR
100	Read from input into DR
101	Print to output from DR
110	If DR is < 0, copy address into PC
111	Stop execution

Preparing To Execute a Program

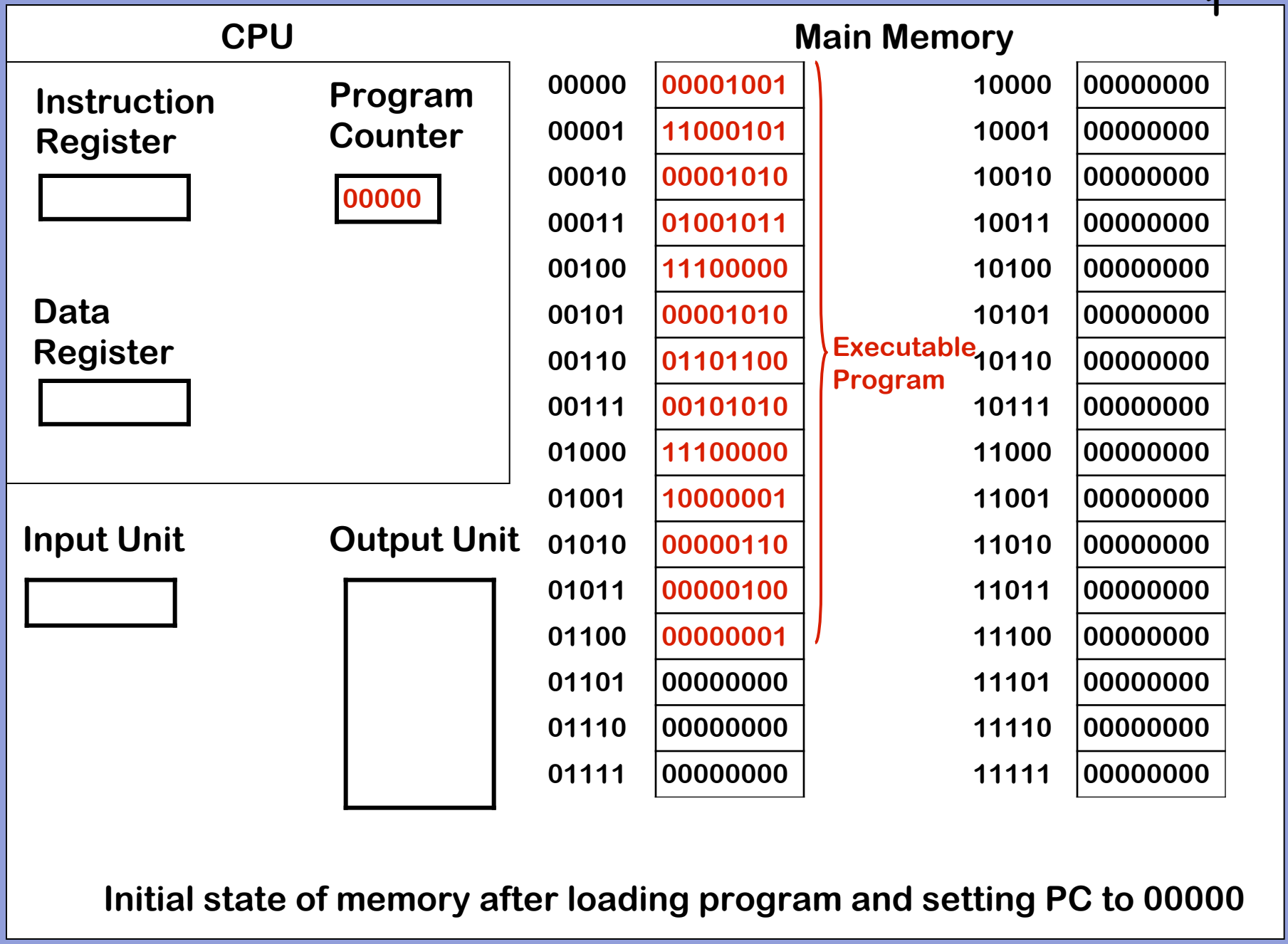
- Your program is first written in a high-level language (e.g., Java): source code
- Converted into machine language: executable

- To run, executable is copied into main memory

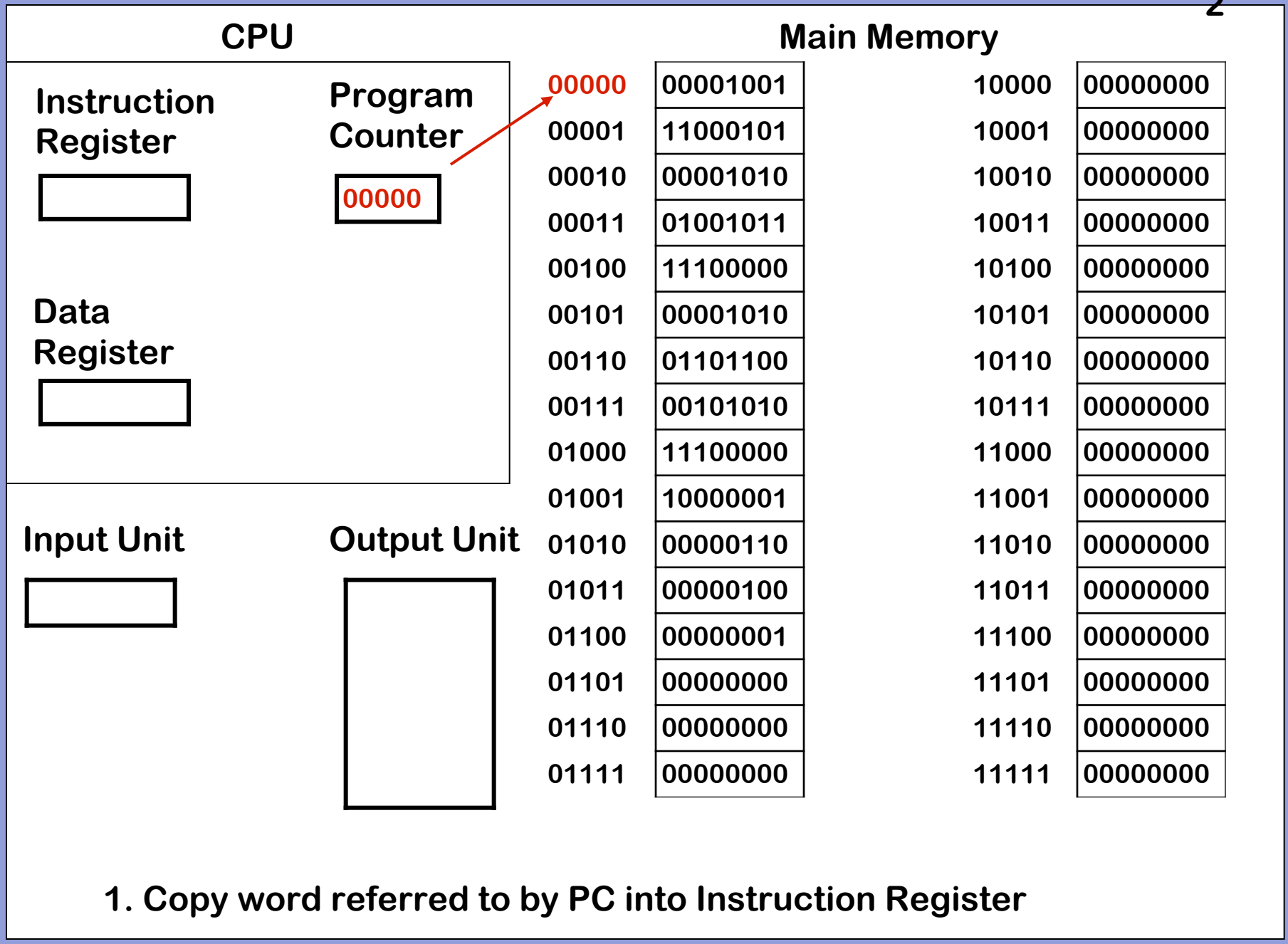
- PC is loaded with the memory address of the first instruction in the executable

Fetch-Execute Cycle

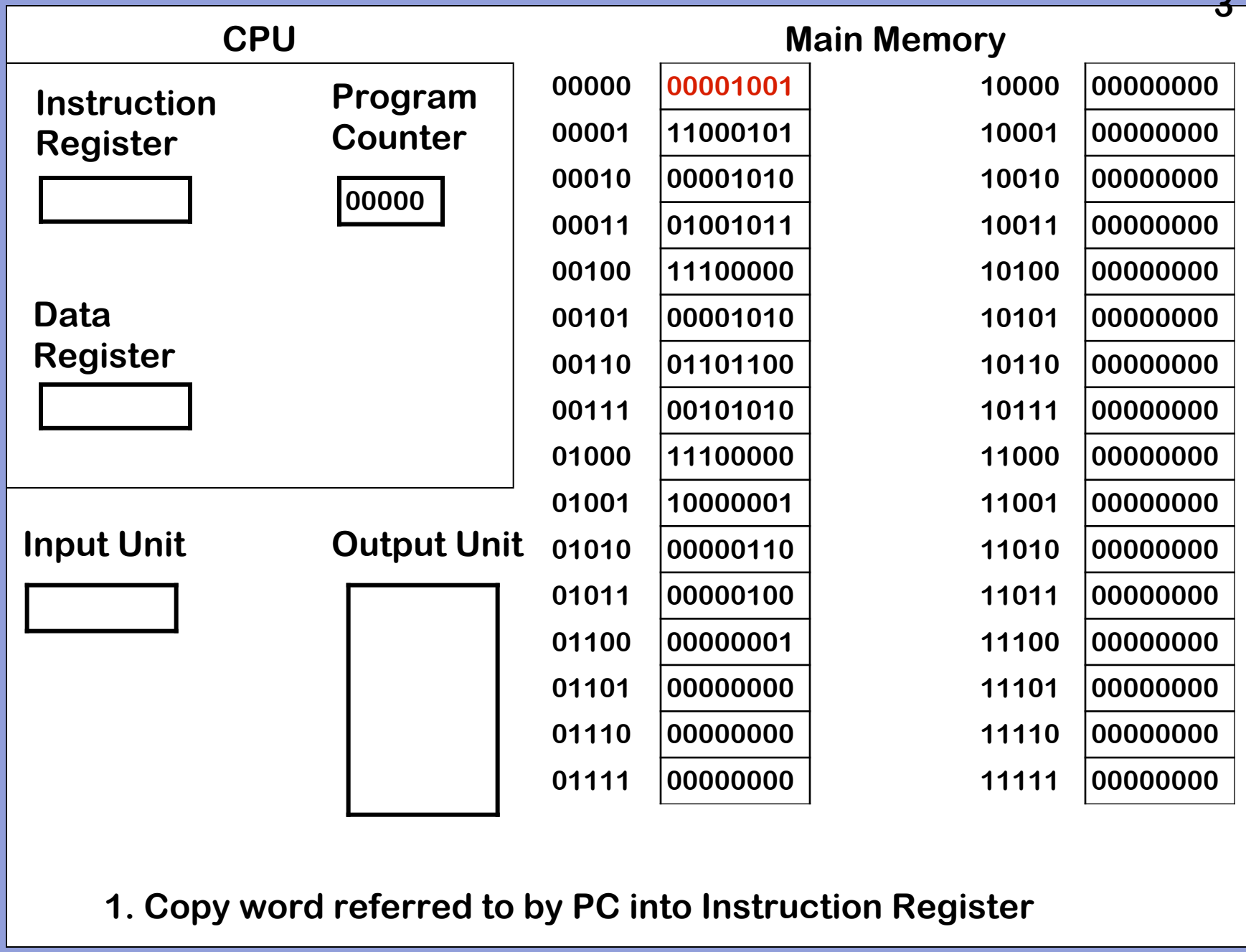
1. Copy the word referred to by the PC into the IR (i.e., fetch)
2. Increment the address stored in the PC
3. Decode & execute the contents of the IR
4. Unless a stop instruction, goto step 1



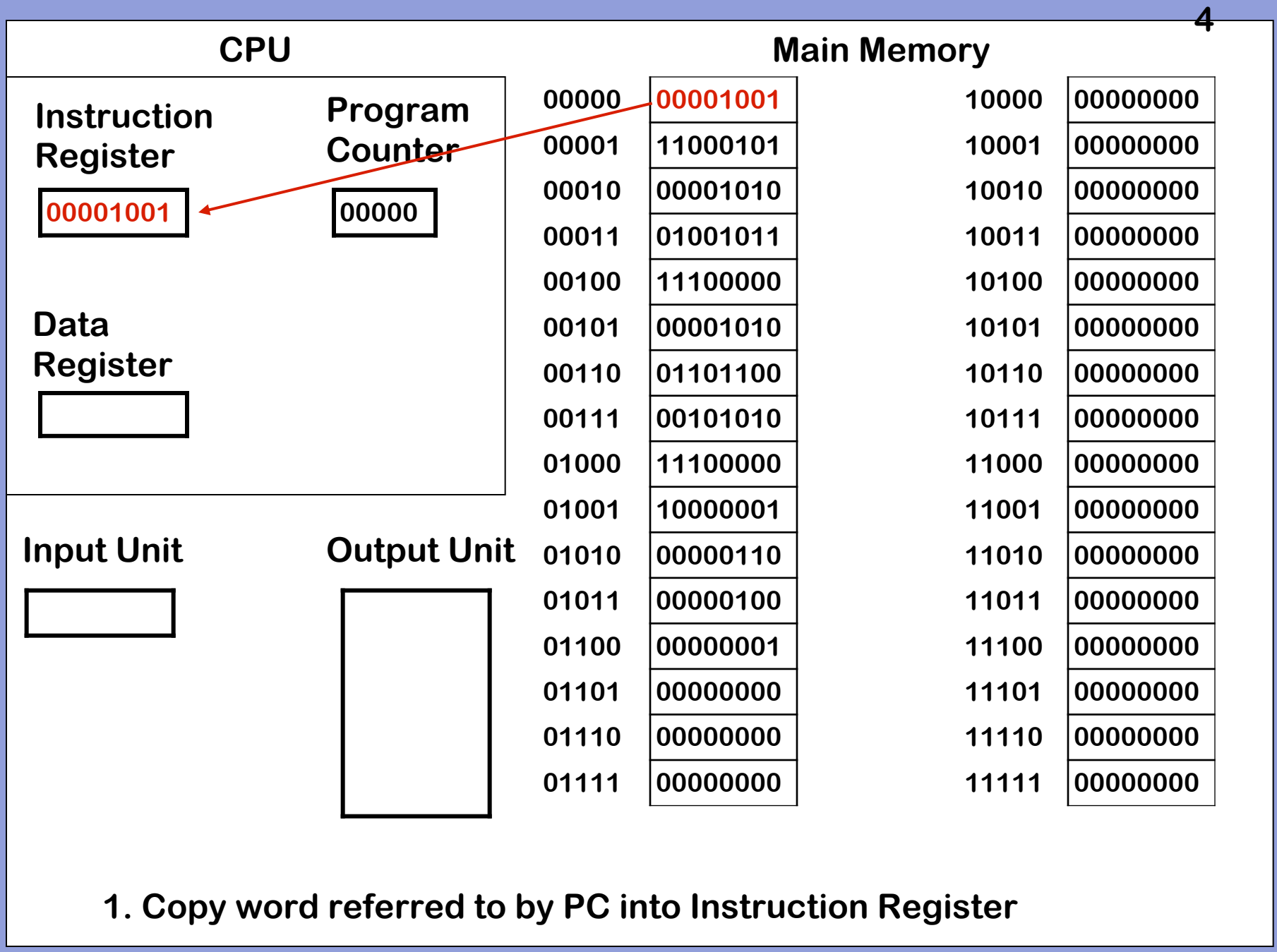
Initial state of memory after loading program and setting PC to 00000



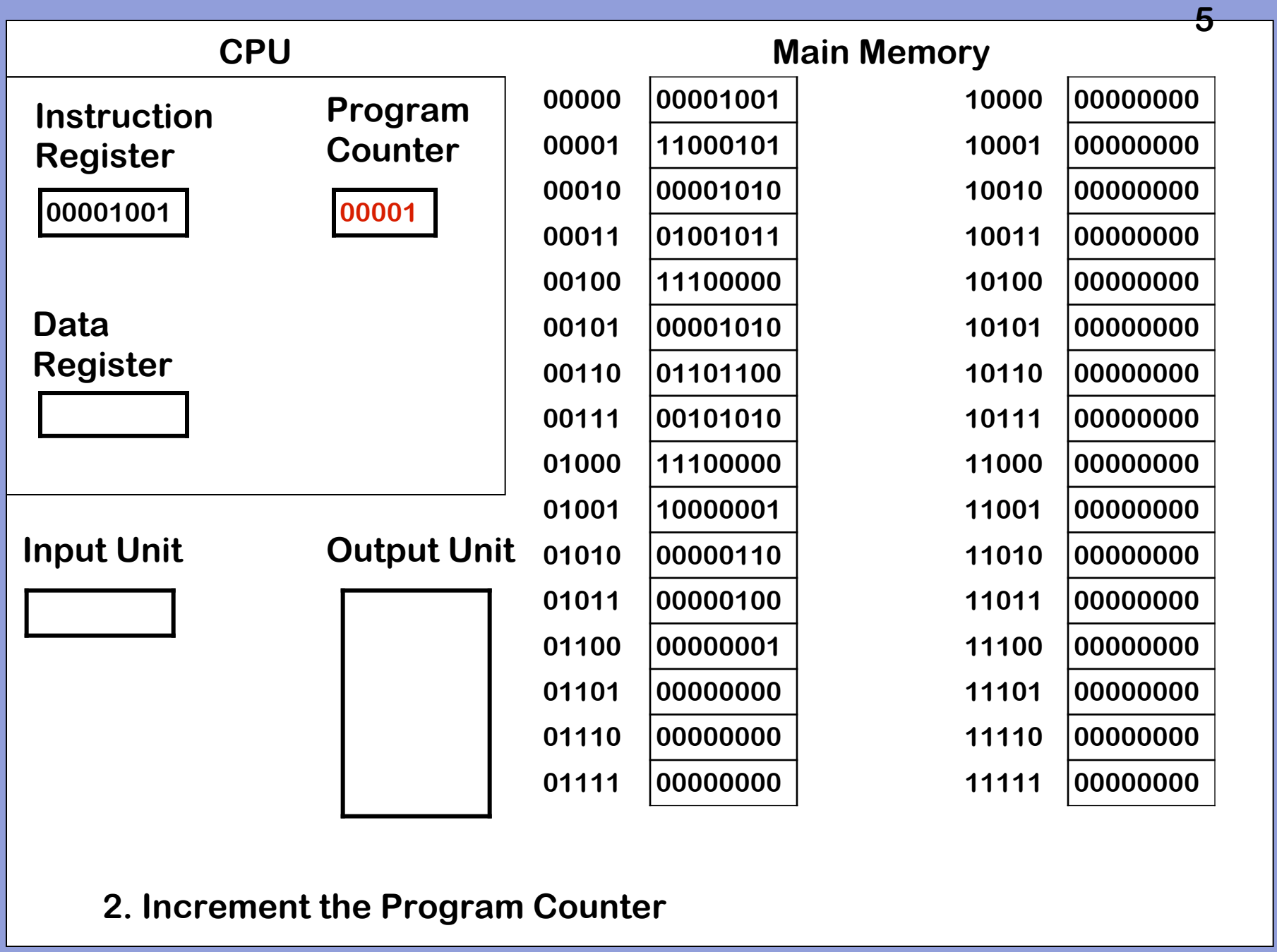
1. Copy word referred to by PC into Instruction Register



1. Copy word referred to by PC into Instruction Register



1. Copy word referred to by PC into Instruction Register



2. Increment the Program Counter

CPU

Instruction Register

00001001

Program Counter

00001

Data Register

Input Unit

Output Unit

Main Memory

00000	00001001
00001	11000101
00010	00001010
00011	01001011
00100	11100000
00101	00001010
00110	01101100
00111	00101010
01000	11100000
01001	10000001
01010	00000110
01011	00000100
01100	00000001
01101	00000000
01110	00000000
01111	00000000

10000	00000000
10001	00000000
10010	00000000
10011	00000000
10100	00000000
10101	00000000
10110	00000000
10111	00000000
11000	00000000
11001	00000000
11010	00000000
11011	00000000
11100	00000000
11101	00000000
11110	00000000
11111	00000000

3. Decode and Execute instruction

CPU

Instruction Register: 00001001

Program Counter: 00001

Data Register:

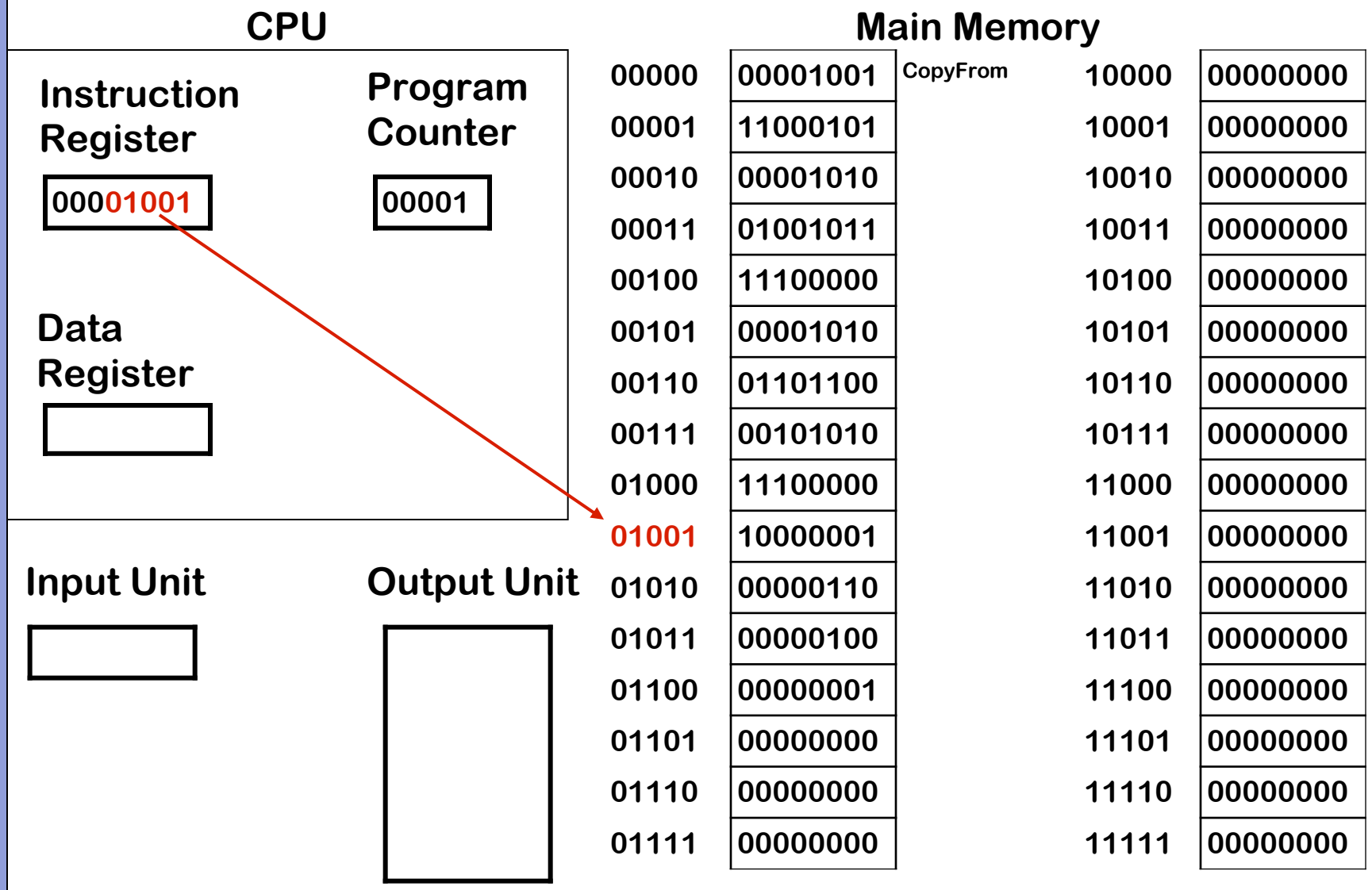
Input Unit

Output Unit

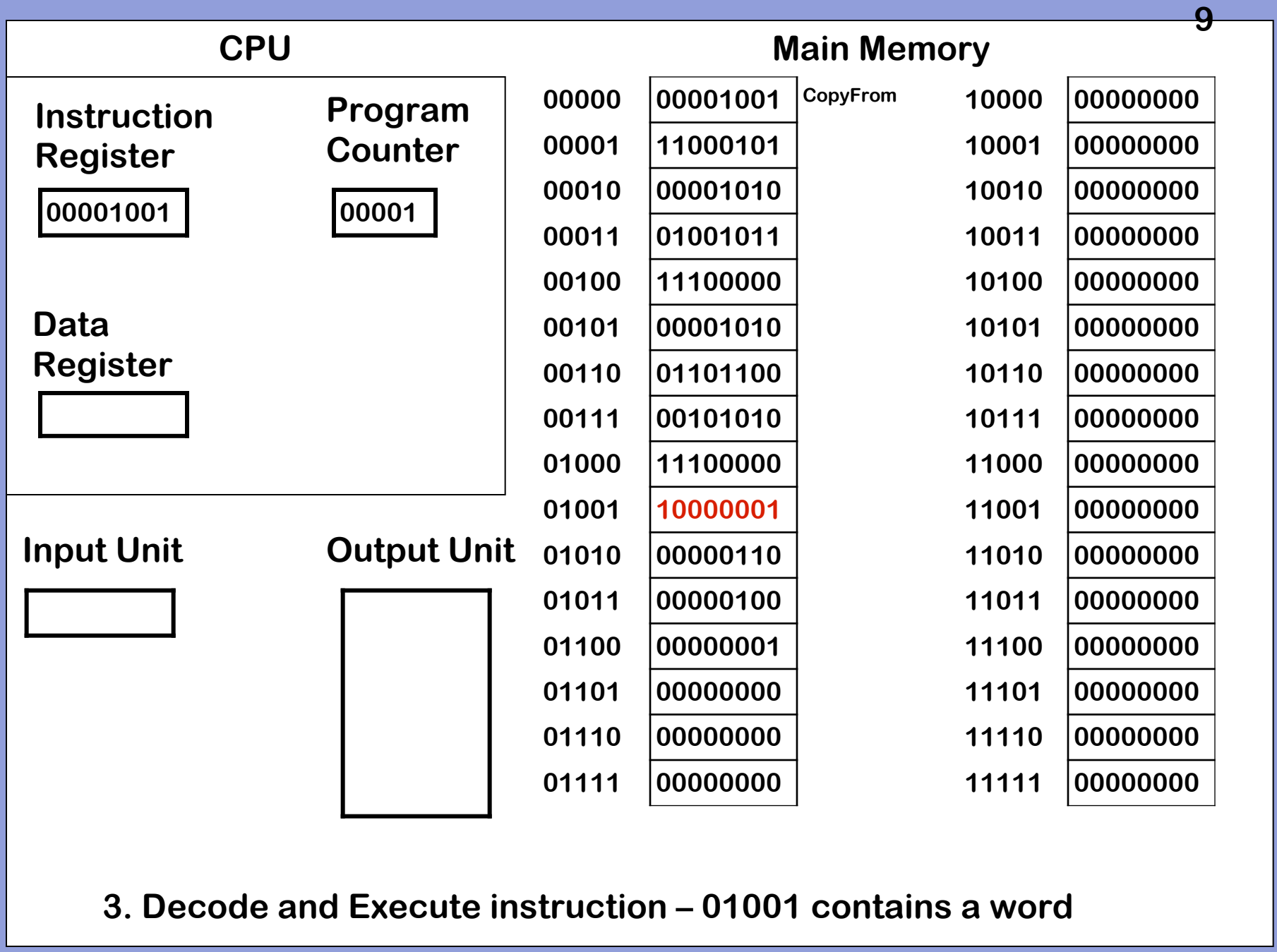
Main Memory

00000	00001001	CopyFrom	10000	00000000
00001	11000101		10001	00000000
00010	00001010		10010	00000000
00011	01001011		10011	00000000
00100	11100000		10100	00000000
00101	00001010		10101	00000000
00110	01101100		10110	00000000
00111	00101010		10111	00000000
01000	11100000		11000	00000000
01001	10000001		11001	00000000
01010	00000110		11010	00000000
01011	00000100		11011	00000000
01100	00000001		11100	00000000
01101	00000000		11101	00000000
01110	00000000		11110	00000000
01111	00000000		11111	00000000

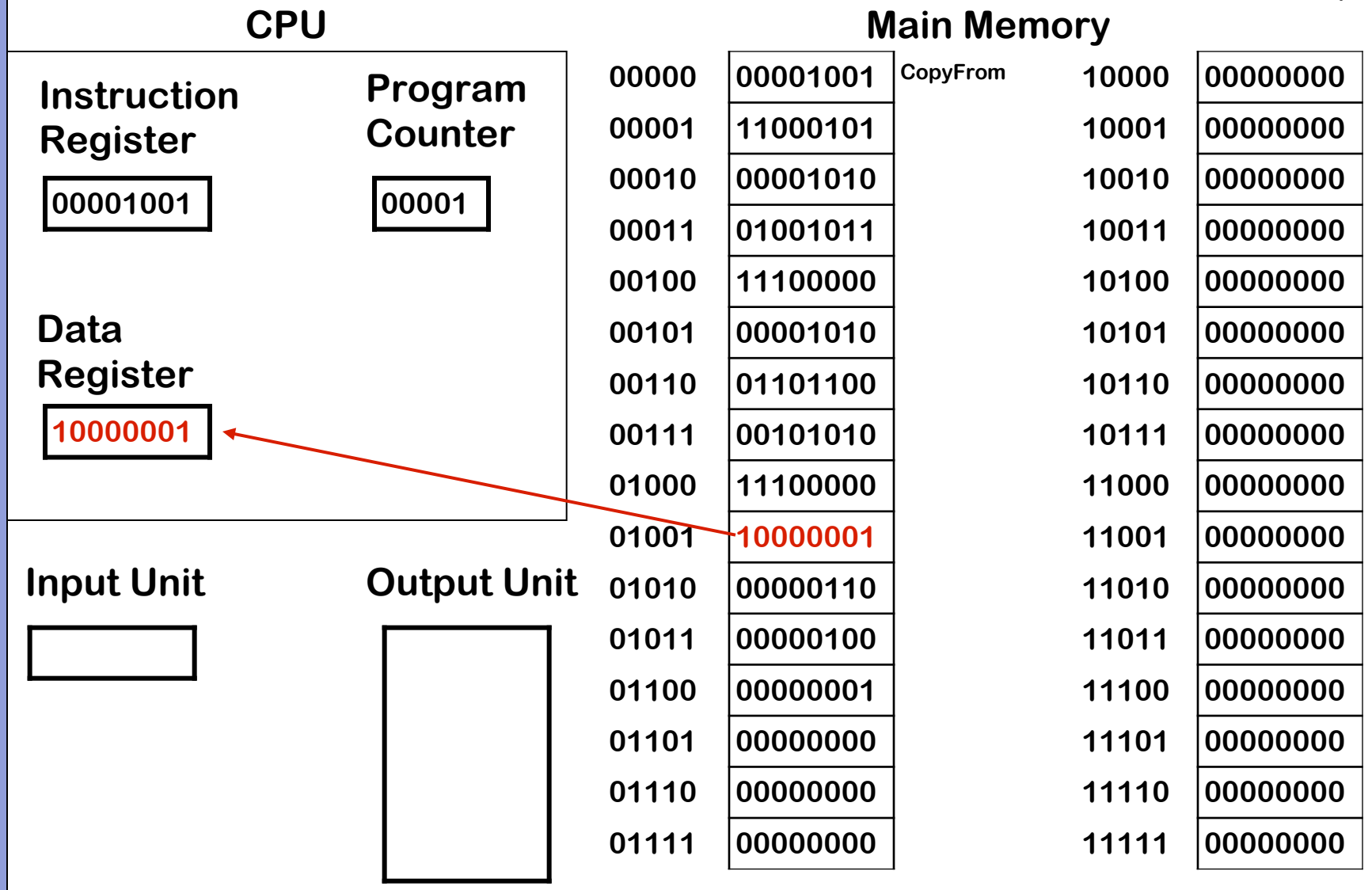
3. Decode and Execute instruction – 000 is op code for CopyFrom



3. Decode and Execute instruction – 01001 is address to copy from



3. Decode and Execute instruction – 01001 contains a word



3. Decode and Execute instruction – Instruction execution is complete

CPU

Instruction Register

00001001

Program Counter

00001

Data Register

10000001

Input Unit

Output Unit

Main Memory

		CopyFrom		
00000	00001001		10000	00000000
00001	11000101		10001	00000000
00010	00001010		10010	00000000
00011	01001011		10011	00000000
00100	11100000		10100	00000000
00101	00001010		10101	00000000
00110	01101100		10110	00000000
00111	00101010		10111	00000000
01000	11100000		11000	00000000
01001	10000001		11001	00000000
01010	00000110		11010	00000000
01011	00000100		11011	00000000
01100	00000001		11100	00000000
01101	00000000		11101	00000000
01110	00000000		11110	00000000
01111	00000000		11111	00000000

Repeat: 1. Copy word referred to by PC to IR

CPU

Instruction Register

11000101

Program Counter

00001

Data Register

10000001

Input Unit

Output Unit

Main Memory

00000	00001001	CopyFrom	10000	00000000
00001	11000101		10001	00000000
00010	00001010		10010	00000000
00011	01001011		10011	00000000
00100	11100000		10100	00000000
00101	00001010		10101	00000000
00110	01101100		10110	00000000
00111	00101010		10111	00000000
01000	11100000		11000	00000000
01001	10000001		11001	00000000
01010	00000110		11010	00000000
01011	00000100		11011	00000000
01100	00000001		11100	00000000
01101	00000000		11101	00000000
01110	00000000		11110	00000000
01111	00000000		11111	00000000

Repeat: 1. Copy word referred to by PC to IR

CPU

Instruction Register

11000101

Program Counter

00010

Data Register

10000001

Input Unit

Output Unit

Main Memory

		CopyFrom		
00000	00001001		10000	00000000
00001	11000101		10001	00000000
00010	00001010		10010	00000000
00011	01001011		10011	00000000
00100	11100000		10100	00000000
00101	00001010		10101	00000000
00110	01101100		10110	00000000
00111	00101010		10111	00000000
01000	11100000		11000	00000000
01001	10000001		11001	00000000
01010	00000110		11010	00000000
01011	00000100		11011	00000000
01100	00000001		11100	00000000
01101	00000000		11101	00000000
01110	00000000		11110	00000000
01111	00000000		11111	00000000

2. Increment PC

CPU

Instruction Register

11000101

Program Counter

00010

Data Register

10000001

Input Unit

Output Unit

Main Memory

00000	00001001	CopyFrom
00001	11000101	
00010	00001010	
00011	01001011	
00100	11100000	
00101	00001010	
00110	01101100	
00111	00101010	
01000	11100000	
01001	10000001	
01010	00000110	
01011	00000100	
01100	00000001	
01101	00000000	
01110	00000000	
01111	00000000	

10000	00000000
10001	00000000
10010	00000000
10011	00000000
10100	00000000
10101	00000000
10110	00000000
10111	00000000
11000	00000000
11001	00000000
11010	00000000
11011	00000000
11100	00000000
11101	00000000
11110	00000000
11111	00000000

3. Decode and execute instruction

CPU

Instruction Register

11000101

Program Counter

00010

Data Register

10000001

Input Unit

Output Unit

Main Memory

00000	00001001	CopyFrom	10000	00000000
00001	11000101	IfNegGoTo	10001	00000000
00010	00001010		10010	00000000
00011	01001011		10011	00000000
00100	11100000		10100	00000000
00101	00001010		10101	00000000
00110	01101100		10110	00000000
00111	00101010		10111	00000000
01000	11100000		11000	00000000
01001	10000001		11001	00000000
01010	00000110		11010	00000000
01011	00000100		11011	00000000
01100	00000001		11100	00000000
01101	00000000		11101	00000000
01110	00000000		11110	00000000
01111	00000000		11111	00000000

3. Decode and execute instruction – 110 is the op code for IfNegGoTo

CPU

Instruction Register

11000101

Program Counter

00010

Data Register

10000001

Input Unit

Output Unit

Main Memory

00000	00001001	CopyFrom	10000	00000000
00001	11000101	IfNegGoTo	10001	00000000
00010	00001010		10010	00000000
00011	01001011		10011	00000000
00100	11100000		10100	00000000
00101	00001010		10101	00000000
00110	01101100		10110	00000000
00111	00101010		10111	00000000
01000	11100000		11000	00000000
01001	10000001		11001	00000000
01010	00000110		11010	00000000
01011	00000100		11011	00000000
01100	00000001		11100	00000000
01101	00000000		11101	00000000
01110	00000000		11110	00000000
01111	00000000		11111	00000000

3. Decode and execute instruction – Check value in data register

CPU

Instruction Register

11000101

Program Counter

00010

Data Register

10000001

Input Unit

Output Unit

Main Memory

00000	00001001	CopyFrom	10000	00000000
00001	11000101	IfNegGoTo	10001	00000000
00010	00001010		10010	00000000
00011	01001011		10011	00000000
00100	11100000		10100	00000000
00101	00001010		10101	00000000
00110	01101100		10110	00000000
00111	00101010		10111	00000000
01000	11100000		11000	00000000
01001	10000001		11001	00000000
01010	00000110		11010	00000000
01011	00000100		11011	00000000
01100	00000001		11100	00000000
01101	00000000		11101	00000000
01110	00000000		11110	00000000
01111	00000000		11111	00000000

3. Decode and execute instruction – DR value is -1

CPU

Instruction Register

11000101

Program Counter

00010

Data Register

10000001

Input Unit

Output Unit

Main Memory

00000	00001001	CopyFrom	10000	00000000
00001	11000101	IfNegGoTo	10001	00000000
00010	00001010		10010	00000000
00011	01001011		10011	00000000
00100	11100000		10100	00000000
00101	00001010		10101	00000000
00110	01101100		10110	00000000
00111	00101010		10111	00000000
01000	11100000		11000	00000000
01001	10000001		11001	00000000
01010	00000110		11010	00000000
01011	00000100		11011	00000000
01100	00000001		11100	00000000
01101	00000000		11101	00000000
01110	00000000		11110	00000000
01111	00000000		11111	00000000

3. Decode and execute instruction – Copy rightmost 5 bits of IR to PC

CPU

Instruction Register

11000101

Program Counter

00101

Data Register

10000001

Input Unit

Output Unit

Main Memory

00000	00001001	CopyFrom	10000	00000000
00001	11000101	IfNegGoTo	10001	00000000
00010	00001010		10010	00000000
00011	01001011		10011	00000000
00100	11100000		10100	00000000
00101	00001010		10101	00000000
00110	01101100		10110	00000000
00111	00101010		10111	00000000
01000	11100000		11000	00000000
01001	10000001		11001	00000000
01010	00000110		11010	00000000
01011	00000100		11011	00000000
01100	00000001		11100	00000000
01101	00000000		11101	00000000
01110	00000000		11110	00000000
01111	00000000		11111	00000000

3. Decode and execute instruction – execution is complete

CPU

Instruction Register

11000101

Program Counter

00101

Data Register

10000001

Input Unit

Output Unit

Main Memory

00000	00001001	CopyFrom	10000	00000000
00001	11000101	IfNegGoTo	10001	00000000
00010	00001010		10010	00000000
00011	01001011		10011	00000000
00100	11100000		10100	00000000
00101	00001010		10101	00000000
00110	01101100		10110	00000000
00111	00101010		10111	00000000
01000	11100000		11000	00000000
01001	10000001		11001	00000000
01010	00000110		11010	00000000
01011	00000100		11011	00000000
01100	00000001		11100	00000000
01101	00000000		11101	00000000
01110	00000000		11110	00000000
01111	00000000		11111	00000000

1. Copy word referred to by PC to IR

CPU

Instruction Register

00001010

Program Counter

00101

Data Register

10000001

Input Unit

Output Unit

Main Memory

00000	00001001	CopyFrom	10000	00000000
00001	11000101	IfNegGoTo	10001	00000000
00010	00001010		10010	00000000
00011	01001011		10011	00000000
00100	11100000		10100	00000000
00101	00001010		10101	00000000
00110	01101100		10110	00000000
00111	00101010		10111	00000000
01000	11100000		11000	00000000
01001	10000001		11001	00000000
01010	00000110		11010	00000000
01011	00000100		11011	00000000
01100	00000001		11100	00000000
01101	00000000		11101	00000000
01110	00000000		11110	00000000
01111	00000000		11111	00000000

1. Copy word referred to by PC to IR

CPU

Instruction Register

00001010

Program Counter

00110

Data Register

10000001

Input Unit

Output Unit

Main Memory

00000	00001001	CopyFrom	10000	00000000
00001	11000101	IfNegGoTo	10001	00000000
00010	00001010		10010	00000000
00011	01001011		10011	00000000
00100	11100000		10100	00000000
00101	00001010		10101	00000000
00110	01101100		10110	00000000
00111	00101010		10111	00000000
01000	11100000		11000	00000000
01001	10000001		11001	00000000
01010	00000110		11010	00000000
01011	00000100		11011	00000000
01100	00000001		11100	00000000
01101	00000000		11101	00000000
01110	00000000		11110	00000000
01111	00000000		11111	00000000

2. Increment PC

CPU

Instruction Register

00001010

Program Counter

00110

Data Register

10000001

Input Unit

Output Unit

Main Memory

00000	00001001	CopyFrom	10000	00000000
00001	11000101	IfNegGoTo	10001	00000000
00010	00001010		10010	00000000
00011	01001011		10011	00000000
00100	11100000		10100	00000000
00101	00001010		10101	00000000
00110	01101100		10110	00000000
00111	00101010		10111	00000000
01000	11100000		11000	00000000
01001	10000001		11001	00000000
01010	00000110		11010	00000000
01011	00000100		11011	00000000
01100	00000001		11100	00000000
01101	00000000		11101	00000000
01110	00000000		11110	00000000
01111	00000000		11111	00000000

3. Decode and execute instruction

CPU

Instruction Register

00001010

Program Counter

00110

Data Register

10000001

Input Unit

Output Unit

Main Memory

00000	00001001	CopyFrom	10000	00000000
00001	11000101	IfNegGoTo	10001	00000000
00010	00001010		10010	00000000
00011	01001011		10011	00000000
00100	11100000		10100	00000000
00101	00001010	CopyFrom	10101	00000000
00110	01101100		10110	00000000
00111	00101010		10111	00000000
01000	11100000		11000	00000000
01001	10000001		11001	00000000
01010	00000110		11010	00000000
01011	00000100		11011	00000000
01100	00000001		11100	00000000
01101	00000000		11101	00000000
01110	00000000		11110	00000000
01111	00000000		11111	00000000

3. Decode and execute instruction – 000 is op code for CopyFrom

CPU

Instruction Register

00001010

Program Counter

00110

Data Register

10000001

Input Unit

Output Unit

Main Memory

00000	00001001	CopyFrom	10000	00000000
00001	11000101	IfNegGoTo	10001	00000000
00010	00001010		10010	00000000
00011	01001011		10011	00000000
00100	11100000		10100	00000000
00101	00001010	CopyFrom	10101	00000000
00110	01101100		10110	00000000
00111	00101010		10111	00000000
01000	11100000		11000	00000000
01001	10000001		11001	00000000
01010	00000110		11010	00000000
01011	00000100		11011	00000000
01100	00000001		11100	00000000
01101	00000000		11101	00000000
01110	00000000		11110	00000000
01111	00000000		11111	00000000

3. Decode and execute instruction

CPU

Instruction Register

00001010

Program Counter

00110

Data Register

00000110

Input Unit

Output Unit

Main Memory

00000	00001001	CopyFrom	10000	00000000
00001	11000101	IfNegGoTo	10001	00000000
00010	00001010		10010	00000000
00011	01001011		10011	00000000
00100	11100000		10100	00000000
00101	00001010	CopyFrom	10101	00000000
00110	01101100		10110	00000000
00111	00101010		10111	00000000
01000	11100000		11000	00000000
01001	10000001		11001	00000000
01010	00000110		11010	00000000
01011	00000100		11011	00000000
01100	00000001		11100	00000000
01101	00000000		11101	00000000
01110	00000000		11110	00000000
01111	00000000		11111	00000000

3. Decode and execute instruction – copy value to DR. Execution complete

CPU

Instruction Register

00001010

Program Counter

00110

Data Register

00000110

Input Unit

Output Unit

Main Memory

00000	00001001	CopyFrom	10000	00000000
00001	11000101	IfNegGoTo	10001	00000000
00010	00001010		10010	00000000
00011	01001011		10011	00000000
00100	11100000		10100	00000000
00101	00001010	CopyFrom	10101	00000000
00110	01101100		10110	00000000
00111	00101010		10111	00000000
01000	11100000		11000	00000000
01001	10000001		11001	00000000
01010	00000110		11010	00000000
01011	00000100		11011	00000000
01100	00000001		11100	00000000
01101	00000000		11101	00000000
01110	00000000		11110	00000000
01111	00000000		11111	00000000

1. Copy word referred to by PC to IR.

CPU

Instruction Register

01101100

Program Counter

00110

Data Register

00000110

Input Unit

Output Unit

Main Memory

00000	00001001	CopyFrom	10000	00000000
00001	11000101	IfNegGoTo	10001	00000000
00010	00001010		10010	00000000
00011	01001011		10011	00000000
00100	11100000		10100	00000000
00101	00001010	CopyFrom	10101	00000000
00110	01101100		10110	00000000
00111	00101010		10111	00000000
01000	11100000		11000	00000000
01001	10000001		11001	00000000
01010	00000110		11010	00000000
01011	00000100		11011	00000000
01100	00000001		11100	00000000
01101	00000000		11101	00000000
01110	00000000		11110	00000000
01111	00000000		11111	00000000

1. Copy word referred to by PC to IR.

CPU

Instruction Register

01101100

Program Counter

00111

Data Register

00000110

Input Unit

Output Unit

Main Memory

00000	00001001	CopyFrom	10000	00000000
00001	11000101	IfNegGoTo	10001	00000000
00010	00001010		10010	00000000
00011	01001011		10011	00000000
00100	11100000		10100	00000000
00101	00001010	CopyFrom	10101	00000000
00110	01101100		10110	00000000
00111	00101010		10111	00000000
01000	11100000		11000	00000000
01001	10000001		11001	00000000
01010	00000110		11010	00000000
01011	00000100		11011	00000000
01100	00000001		11100	00000000
01101	00000000		11101	00000000
01110	00000000		11110	00000000
01111	00000000		11111	00000000

2. Increment PC

CPU

Instruction Register

01101100

Program Counter

00111

Data Register

00000110

Input Unit

Output Unit

Main Memory

00000	00001001	CopyFrom	10000	00000000
00001	11000101	IfNegGoTo	10001	00000000
00010	00001010		10010	00000000
00011	01001011		10011	00000000
00100	11100000		10100	00000000
00101	00001010	CopyFrom	10101	00000000
00110	01101100		10110	00000000
00111	00101010		10111	00000000
01000	11100000		11000	00000000
01001	10000001		11001	00000000
01010	00000110		11010	00000000
01011	00000100		11011	00000000
01100	00000001		11100	00000000
01101	00000000		11101	00000000
01110	00000000		11110	00000000
01111	00000000		11111	00000000

3. Decode and execute instruction

CPU

Instruction Register

01101100

Program Counter

00111

Data Register

00000110

Input Unit

Output Unit

Main Memory

00000	00001001	CopyFrom	10000	00000000
00001	11000101	IfNegGoTo	10001	00000000
00010	00001010		10010	00000000
00011	01001011		10011	00000000
00100	11100000		10100	00000000
00101	00001010	CopyFrom	10101	00000000
00110	01101100	Subtract	10110	00000000
00111	00101010		10111	00000000
01000	11100000		11000	00000000
01001	10000001		11001	00000000
01010	00000110		11010	00000000
01011	00000100		11011	00000000
01100	00000001		11100	00000000
01101	00000000		11101	00000000
01110	00000000		11110	00000000
01111	00000000		11111	00000000

3. Decode and execute instruction – 011 is Subtract

CPU

Instruction Register

01101100

Program Counter

00111

Data Register

00000110

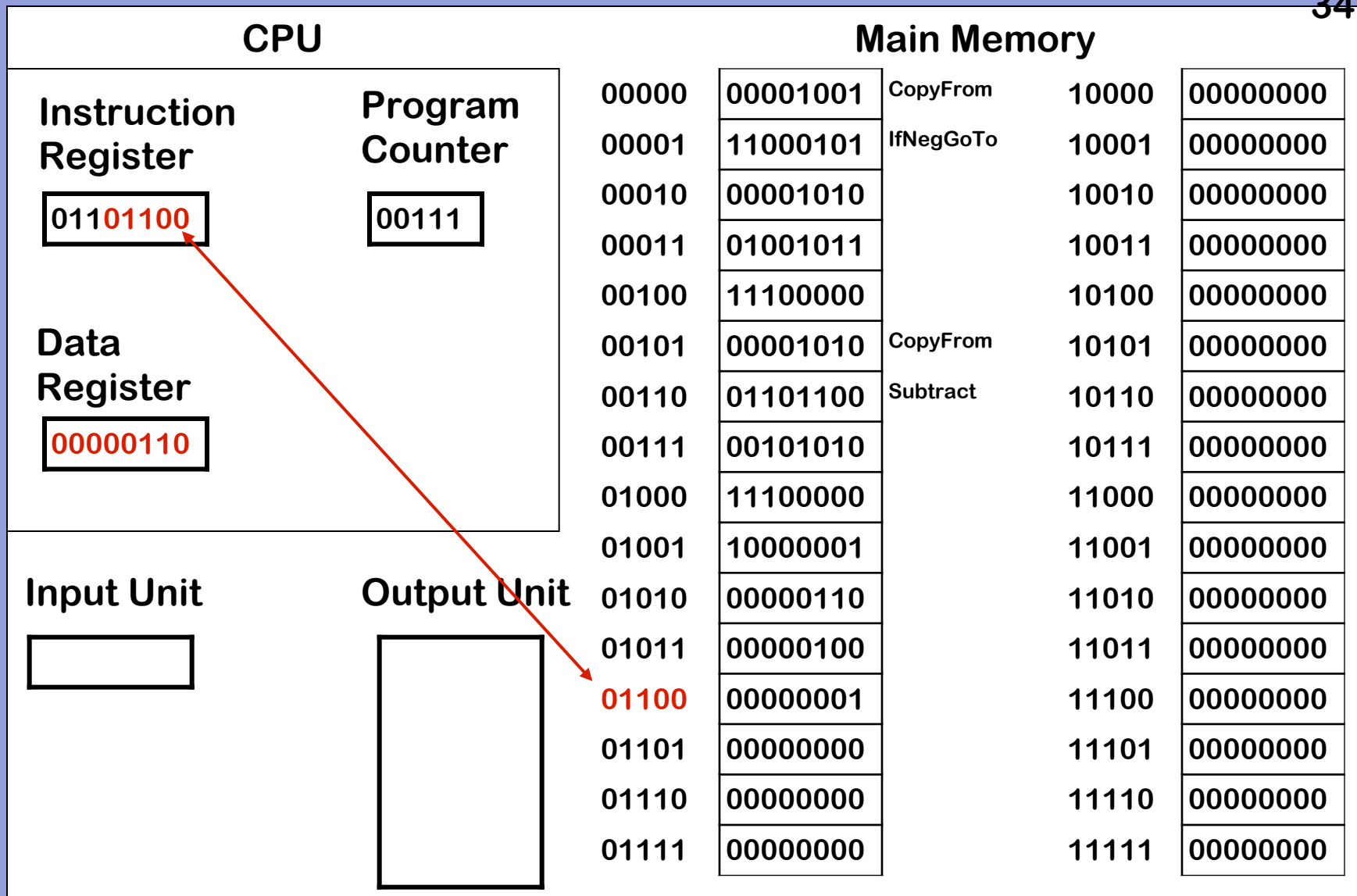
Input Unit

Output Unit

Main Memory

00000	00001001	CopyFrom	10000	00000000
00001	11000101	IfNegGoTo	10001	00000000
00010	00001010		10010	00000000
00011	01001011		10011	00000000
00100	11100000		10100	00000000
00101	00001010	CopyFrom	10101	00000000
00110	01101100	Subtract	10110	00000000
00111	00101010		10111	00000000
01000	11100000		11000	00000000
01001	10000001		11001	00000000
01010	00000110		11010	00000000
01011	00000100		11011	00000000
01100	00000001		11100	00000000
01101	00000000		11101	00000000
01110	00000000		11110	00000000
01111	00000000		11111	00000000

3. Decode and execute instruction – data register is first operand



3. Decode and execute instruction – word at 01100 is second operand

CPU

Instruction Register

01101100

Program Counter

00111

Data Register

00000110

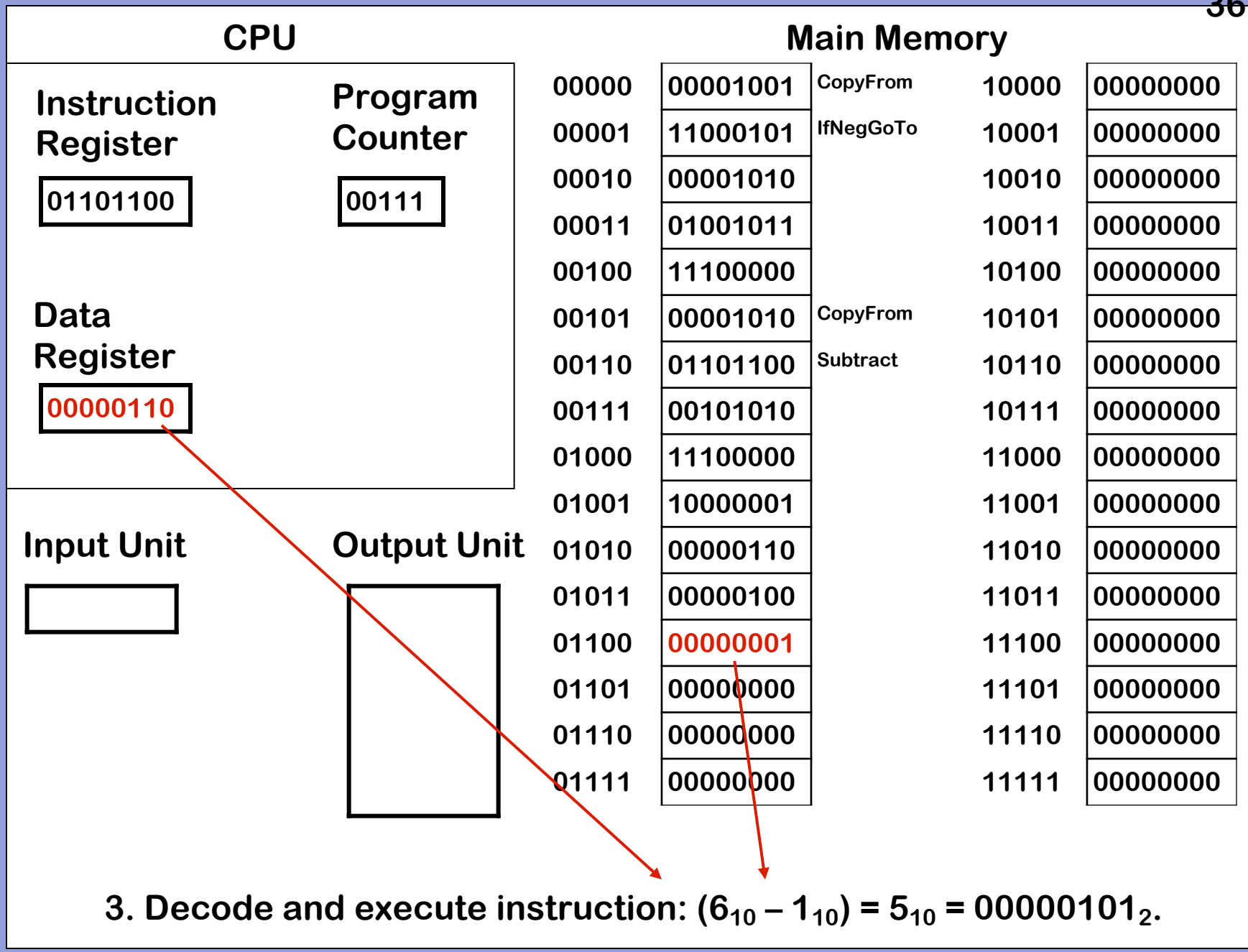
Input Unit

Output Unit

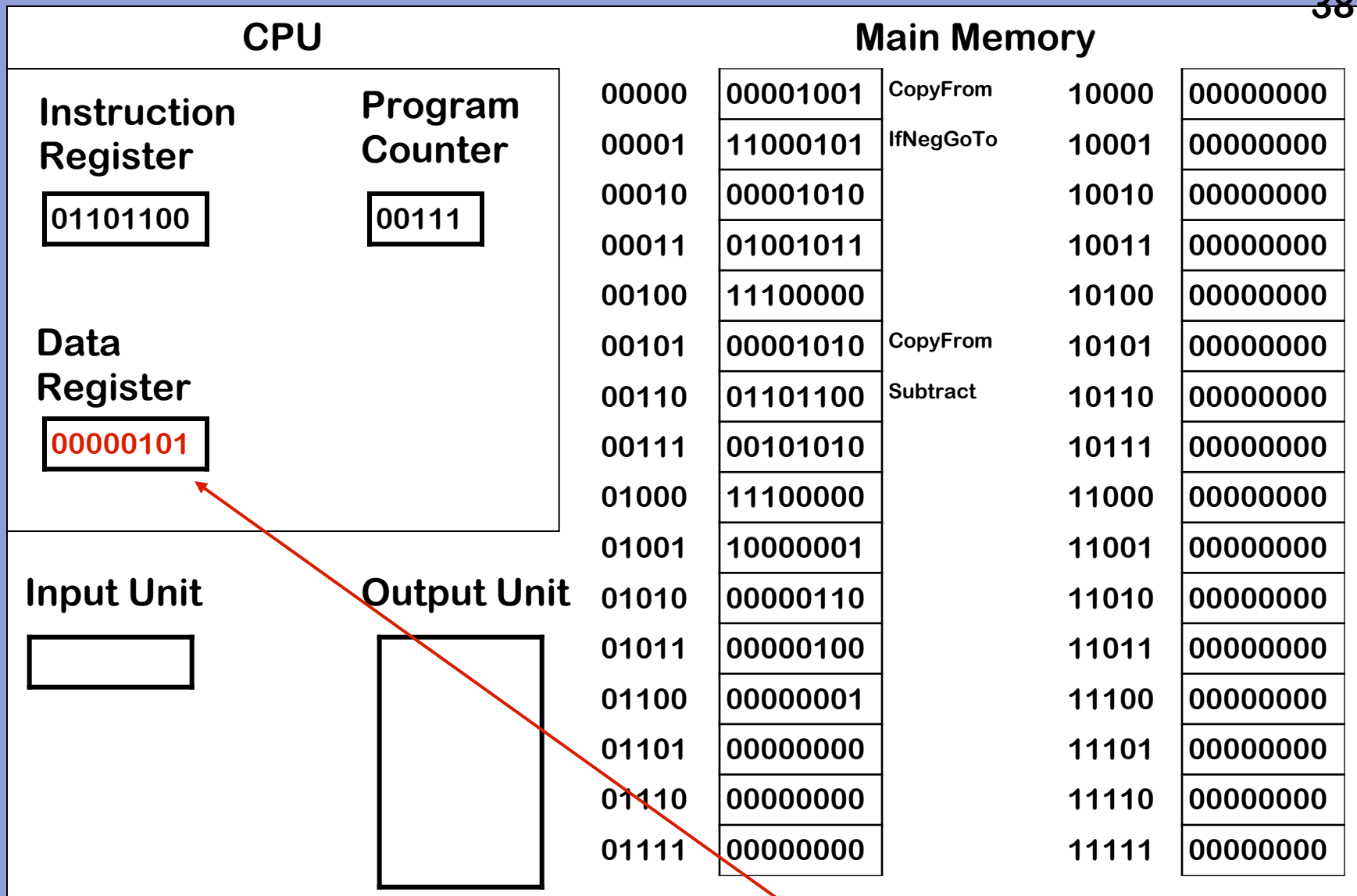
Main Memory

00000	00001001	CopyFrom	10000	00000000
00001	11000101	IfNegGoTo	10001	00000000
00010	00001010		10010	00000000
00011	01001011		10011	00000000
00100	11100000		10100	00000000
00101	00001010	CopyFrom	10101	00000000
00110	01101100	Subtract	10110	00000000
00111	00101010		10111	00000000
01000	11100000		11000	00000000
01001	10000001		11001	00000000
01010	00000110		11010	00000000
01011	00000100		11011	00000000
01100	00000001		11100	00000000
01101	00000000		11101	00000000
01110	00000000		11110	00000000
01111	00000000		11111	00000000

3. Decode and execute instruction – word at 01100 is second operand



3. Decode and execute instruction: $(6_{10} - 1_{10}) = 5_{10} = 00000101_2$.



3. Decode and execute instruction: 5_{10} = 00000101_2. Result is stored in DR

CPU

Instruction Register

01101100

Program Counter

00111

Data Register

00000101

Input Unit

Output Unit

Main Memory

00000	00001001	CopyFrom	10000	00000000	
00001	11000101	IfNegGoTo	10001	00000000	
00010	00001010		10010	00000000	
00011	01001011		10011	00000000	
00100	11100000		10100	00000000	
00101	00001010	CopyFrom	10101	00000000	
00110	01101100	Subtract	10110	00000000	
00111	00101010		10111	00000000	
01000	11100000		11000	00000000	
01001	10000001		11001	00000000	
01010	00000110		11010	00000000	
01011	00000100		11011	00000000	
01100	00000001		11100	00000000	
01101	00000000		11101	00000000	
01110	00000000		11110	00000000	
01111	00000000		11111	00000000	

1. Copy word referred to by PC to IR.

CPU

Instruction Register

00101010

Program Counter

00111

Data Register

00000101

Input Unit

Output Unit

Main Memory

00000	00001001	CopyFrom	10000	00000000
00001	11000101	IfNegGoTo	10001	00000000
00010	00001010		10010	00000000
00011	01001011		10011	00000000
00100	11100000		10100	00000000
00101	00001010	CopyFrom	10101	00000000
00110	01101100	Subtract	10110	00000000
00111	00101010		10111	00000000
01000	11100000		11000	00000000
01001	10000001		11001	00000000
01010	00000110		11010	00000000
01011	00000100		11011	00000000
01100	00000001		11100	00000000
01101	00000000		11101	00000000
01110	00000000		11110	00000000
01111	00000000		11111	00000000

1. Copy word referred to by PC to IR.

CPU

Instruction Register

00101010

Program Counter

01000

Data Register

00000101

Input Unit

Output Unit

Main Memory

00000	00001001	CopyFrom	10000	00000000
00001	11000101	IfNegGoTo	10001	00000000
00010	00001010		10010	00000000
00011	01001011		10011	00000000
00100	11100000		10100	00000000
00101	00001010	CopyFrom	10101	00000000
00110	01101100	Subtract	10110	00000000
00111	00101010		10111	00000000
01000	11100000		11000	00000000
01001	10000001		11001	00000000
01010	00000110		11010	00000000
01011	00000100		11011	00000000
01100	00000001		11100	00000000
01101	00000000		11101	00000000
01110	00000000		11110	00000000
01111	00000000		11111	00000000

2. Increment PC

CPU

Instruction Register: 00101010

Program Counter: 01000

Data Register: 00000101

Input Unit

Output Unit

Main Memory

00000	00001001	CopyFrom	10000	00000000	
00001	11000101	IfNegGoTo	10001	00000000	
00010	00001010		10010	00000000	
00011	01001011		10011	00000000	
00100	11100000		10100	00000000	
00101	00001010	CopyFrom	10101	00000000	
00110	01101100	Subtract	10110	00000000	
00111	00101010		10111	00000000	
01000	11100000		11000	00000000	
01001	10000001		11001	00000000	
01010	00000110		11010	00000000	
01011	00000100		11011	00000000	
01100	00000001		11100	00000000	
01101	00000000		11101	00000000	
01110	00000000		11110	00000000	
01111	00000000		11111	00000000	

3. Decode and execute instruction

CPU

Instruction Register

00101010

Program Counter

01000

Data Register

00000101

Input Unit

Output Unit

Main Memory

00000	00001001	CopyFrom	10000	00000000
00001	11000101	IfNegGoTo	10001	00000000
00010	00001010		10010	00000000
00011	01001011		10011	00000000
00100	11100000		10100	00000000
00101	00001010	CopyFrom	10101	00000000
00110	01101100	Subtract	10110	00000000
00111	00101010	CopyTo	10111	00000000
01000	11100000		11000	00000000
01001	10000001		11001	00000000
01010	00000110		11010	00000000
01011	00000100		11011	00000000
01100	00000001		11100	00000000
01101	00000000		11101	00000000
01110	00000000		11110	00000000
01111	00000000		11111	00000000

3. Decode and execute instruction – 001 is CopyTo

CPU

Instruction Register

00101010

Program Counter

01000

Data Register

00000101

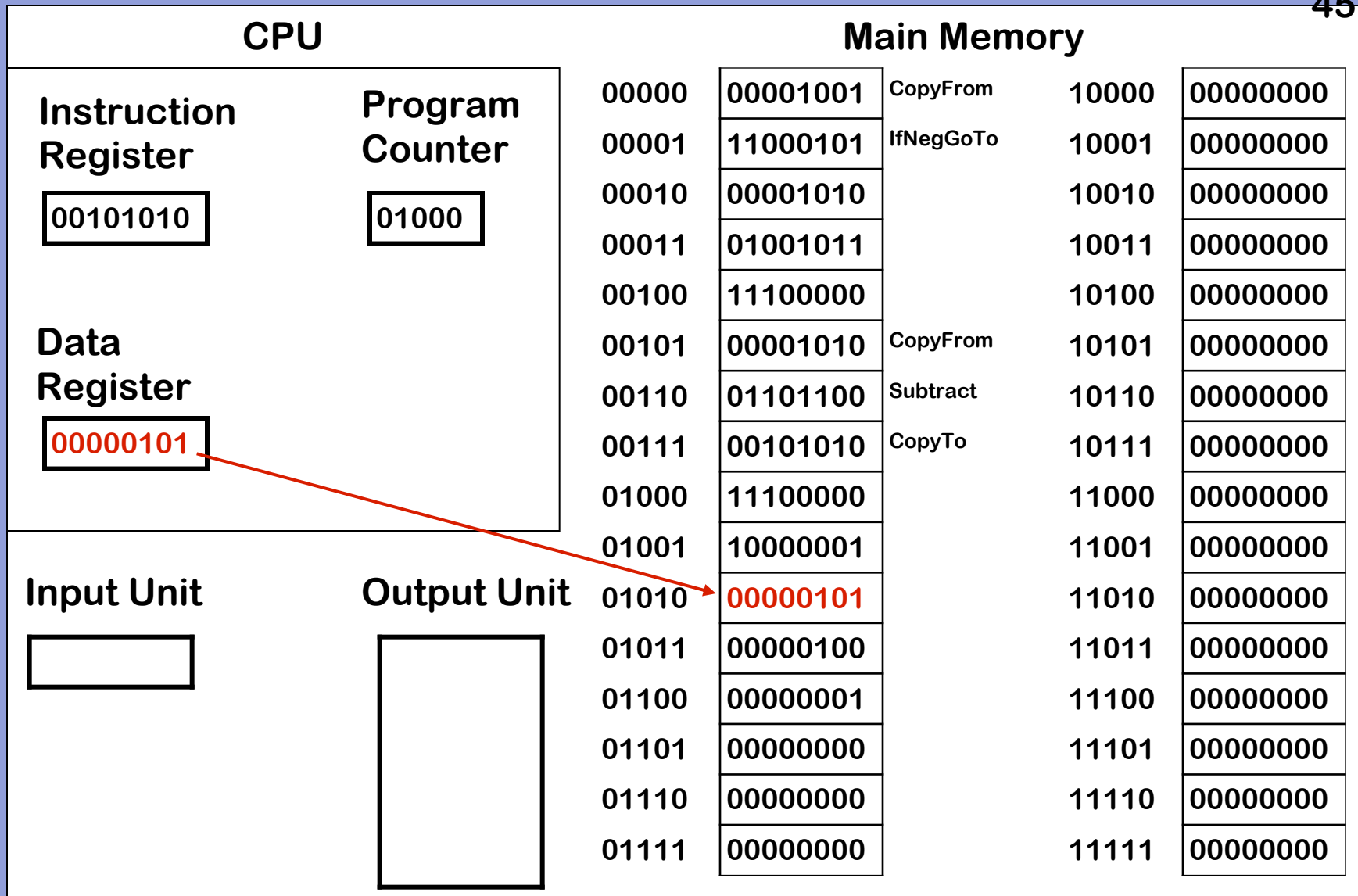
Input Unit

Output Unit

Main Memory

00000	00001001	CopyFrom	10000	00000000
00001	11000101	IfNegGoTo	10001	00000000
00010	00001010		10010	00000000
00011	01001011		10011	00000000
00100	11100000		10100	00000000
00101	00001010	CopyFrom	10101	00000000
00110	01101100	Subtract	10110	00000000
00111	00101010	CopyTo	10111	00000000
01000	11100000		11000	00000000
01001	10000001		11001	00000000
01010	00000110		11010	00000000
01011	00000100		11011	00000000
01100	00000001		11100	00000000
01101	00000000		11101	00000000
01110	00000000		11110	00000000
01111	00000000		11111	00000000

3. Decode and execute instruction – 01010 is target location



3. Decode and execute instruction – value in DR copied to memory

CPU

Instruction Register

00101010

Program Counter

01000

Data Register

00000101

Input Unit

Output Unit

Main Memory

00000	00001001	CopyFrom	10000	00000000	
00001	11000101	IfNegGoTo	10001	00000000	
00010	00001010		10010	00000000	
00011	01001011		10011	00000000	
00100	11100000		10100	00000000	
00101	00001010	CopyFrom	10101	00000000	
00110	01101100	Subtract	10110	00000000	
00111	00101010	CopyTo	10111	00000000	
01000	11100000		11000	00000000	
01001	10000001		11001	00000000	
01010	00000101		11010	00000000	
01011	00000100		11011	00000000	
01100	00000001		11100	00000000	
01101	00000000		11101	00000000	
01110	00000000		11110	00000000	
01111	00000000		11111	00000000	

1. Copy word referred to by PC to IR

CPU

Instruction Register

11100000

Program Counter

01000

Data Register

00000101

Input Unit

Output Unit

Main Memory

00000	00001001	CopyFrom	10000	00000000
00001	11000101	IfNegGoTo	10001	00000000
00010	00001010		10010	00000000
00011	01001011		10011	00000000
00100	11100000		10100	00000000
00101	00001010	CopyFrom	10101	00000000
00110	01101100	Subtract	10110	00000000
00111	00101010	CopyTo	10111	00000000
01000	11100000		11000	00000000
01001	10000001		11001	00000000
01010	00000101		11010	00000000
01011	00000100		11011	00000000
01100	00000001		11100	00000000
01101	00000000		11101	00000000
01110	00000000		11110	00000000
01111	00000000		11111	00000000

1. Copy word referred to by PC to IR

CPU

Instruction Register

11100000

Program Counter

01001

Data Register

00000101

Input Unit

Output Unit

Main Memory

00000	00001001	CopyFrom	10000	00000000
00001	11000101	IfNegGoTo	10001	00000000
00010	00001010		10010	00000000
00011	01001011		10011	00000000
00100	11100000		10100	00000000
00101	00001010	CopyFrom	10101	00000000
00110	01101100	Subtract	10110	00000000
00111	00101010	CopyTo	10111	00000000
01000	11100000		11000	00000000
01001	10000001		11001	00000000
01010	00000101		11010	00000000
01011	00000100		11011	00000000
01100	00000001		11100	00000000
01101	00000000		11101	00000000
01110	00000000		11110	00000000
01111	00000000		11111	00000000

2. Increment PC

CPU

Instruction Register

11100000

Program Counter

01001

Data Register

00000101

Input Unit

Output Unit

Main Memory

00000	00001001	CopyFrom	10000	00000000
00001	11000101	IfNegGoTo	10001	00000000
00010	00001010		10010	00000000
00011	01001011		10011	00000000
00100	11100000		10100	00000000
00101	00001010	CopyFrom	10101	00000000
00110	01101100	Subtract	10110	00000000
00111	00101010	CopyTo	10111	00000000
01000	11100000		11000	00000000
01001	10000001		11001	00000000
01010	00000101		11010	00000000
01011	00000100		11011	00000000
01100	00000001		11100	00000000
01101	00000000		11101	00000000
01110	00000000		11110	00000000
01111	00000000		11111	00000000

3. Decode and execute instruction

CPU

Instruction Register

11100000

Program Counter

01001

Data Register

00000101

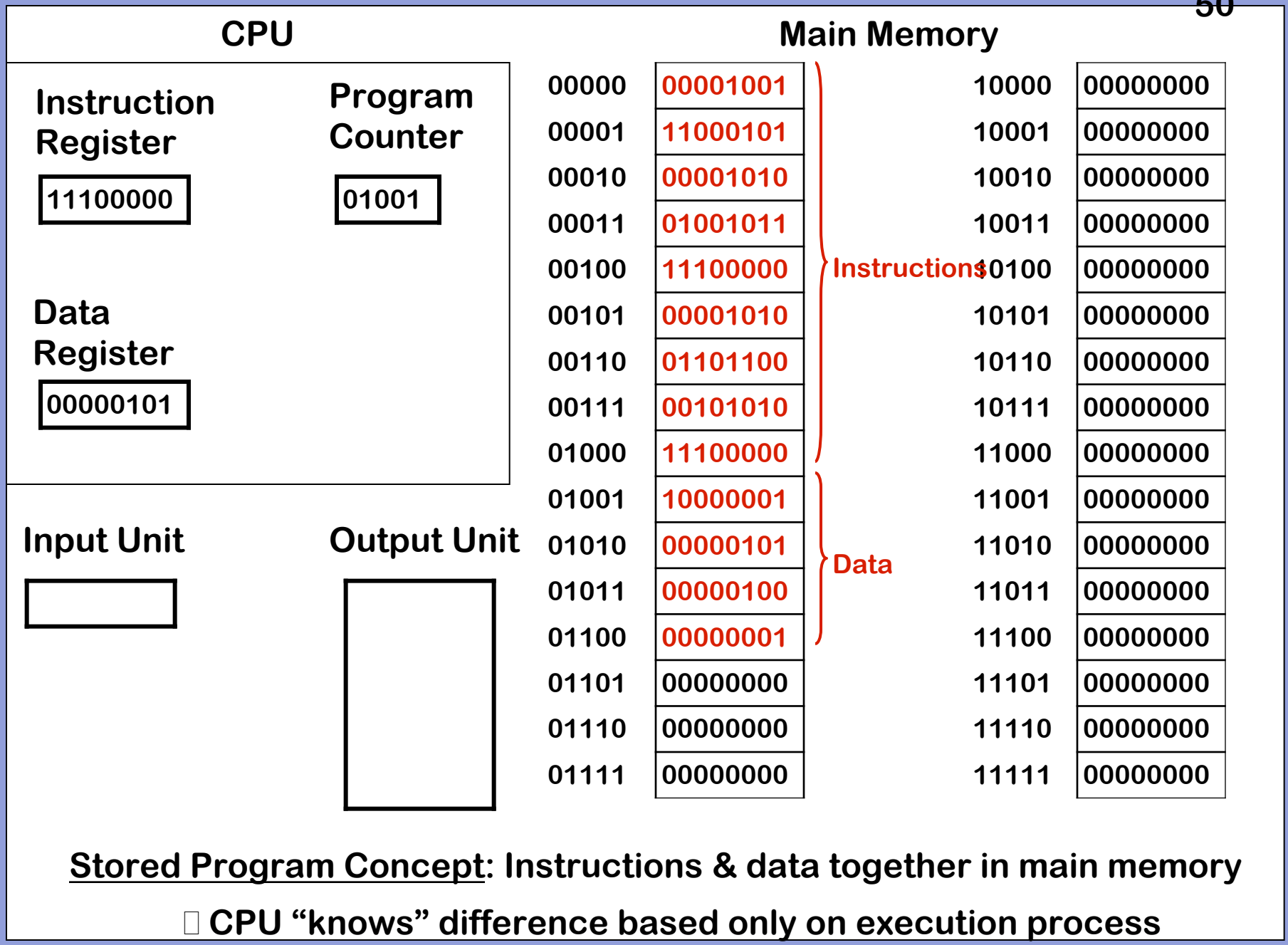
Input Unit

Output Unit

Main Memory

00000	00001001	CopyFrom	10000	00000000
00001	11000101	IfNegGoTo	10001	00000000
00010	00001010		10010	00000000
00011	01001011		10011	00000000
00100	11100000		10100	00000000
00101	00001010	CopyFrom	10101	00000000
00110	01101100	Subtract	10110	00000000
00111	00101010	CopyTo	10111	00000000
01000	11100000	Stop	11000	00000000
01001	10000001		11001	00000000
01010	00000101		11010	00000000
01011	00000100		11011	00000000
01100	00000001		11100	00000000
01101	00000000		11101	00000000
01110	00000000		11110	00000000
01111	00000000		11111	00000000

3. Decode and execute instruction – 111 is op code for Stop



Stored Program Concept: Instructions & data together in main memory

- CPU "knows" difference based only on execution process

[8 points] Consider the assembly language program (from the Woody instruction set architecture) shown below. (It uses variable names rather than binary addresses for convenience, so simply consider A, B, One, and Zero to be memory locations.)

```
Loop:     CopyFrom   A
          Subtract   B
          IfNegGoTo  DoStuff
          CopyTo     A
          CopyFrom   Zero
          Subtract   One
          IfNegGoTo  Loop
DoStuff:  CopyFrom   A
          Print
          Stop
A:        2
B:        4
One:      1
Zero:     0
```

(a) What value(s) is(are) sent to the output unit? (You do **not** have to show the fetch-execute cycle of the program.)

(b) If memory location `A` initially contains 5 and `B` initially contains 2, what value(s) is(are) sent to the output unit?

(c) If memory location `A` initially contains 7 and `B` initially contains 3, what value(s) is(are) sent to the output unit?

(d) *Very briefly* (in **four** words or less) describe the purpose of this program.