ASCS ADAPTIVE & SECURE COMPUTING SYSTEMS LABORATORY

Ira A. Fulton Schools of Engineering
Arizona State University

CSE 598
Secure Microkernel Design

Introduction to the fundamentals of computer architecture using the RISC-V ISA

Prof. Michel A. Kinsy

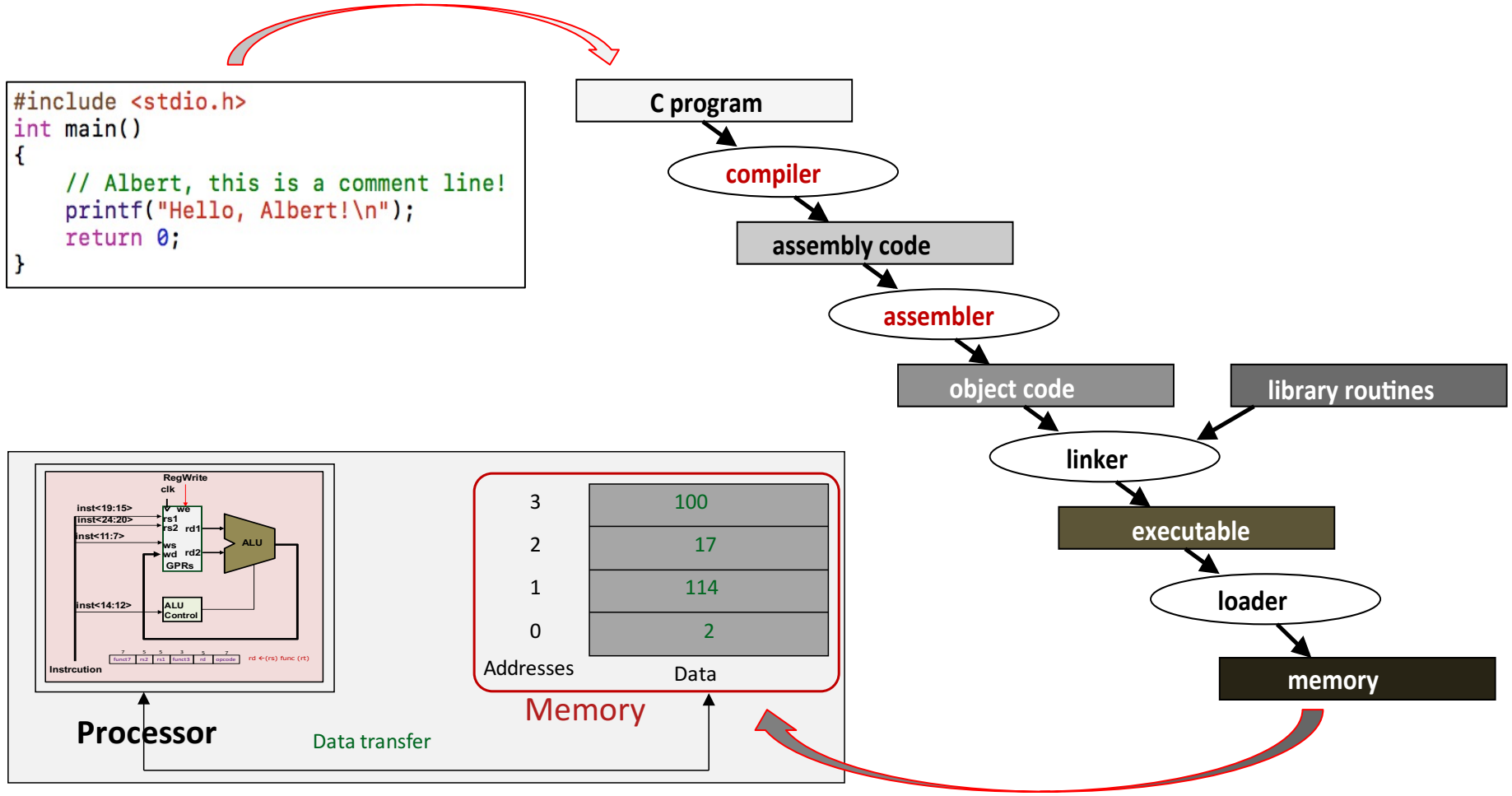
STAM Center
SECURE, TRUSTED, AND ASSURED MICROELECTRONICS

CSE 598
Secure Microkernel Design

Assembly Language Programming

Prof. Michel A. Kinsy

The Big Picture

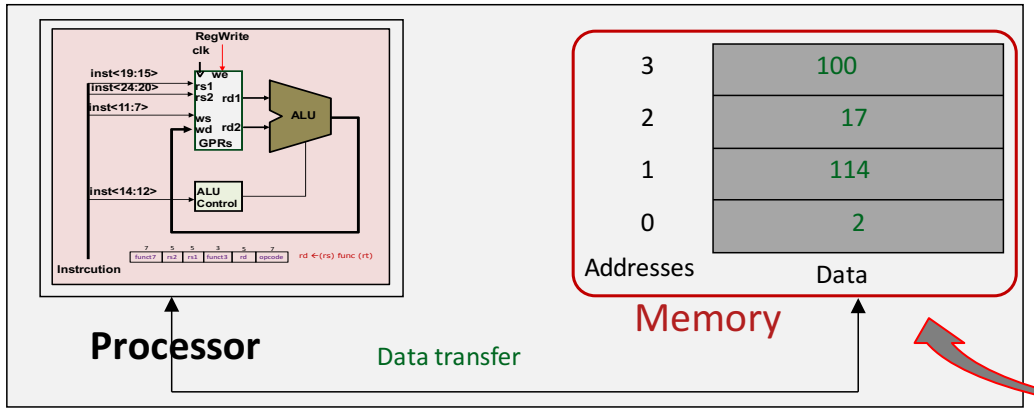


The Big Picture

```c
#include <stdio.h>
int main()
{
    // Albert, this is a comment line!
    printf("Hello, Albert!\n");
    return 0;
}
```

C program → compiler → assembly code → assembler → object code + library routines → linker → executable → loader → memory

We are systematically answering this set of questions!



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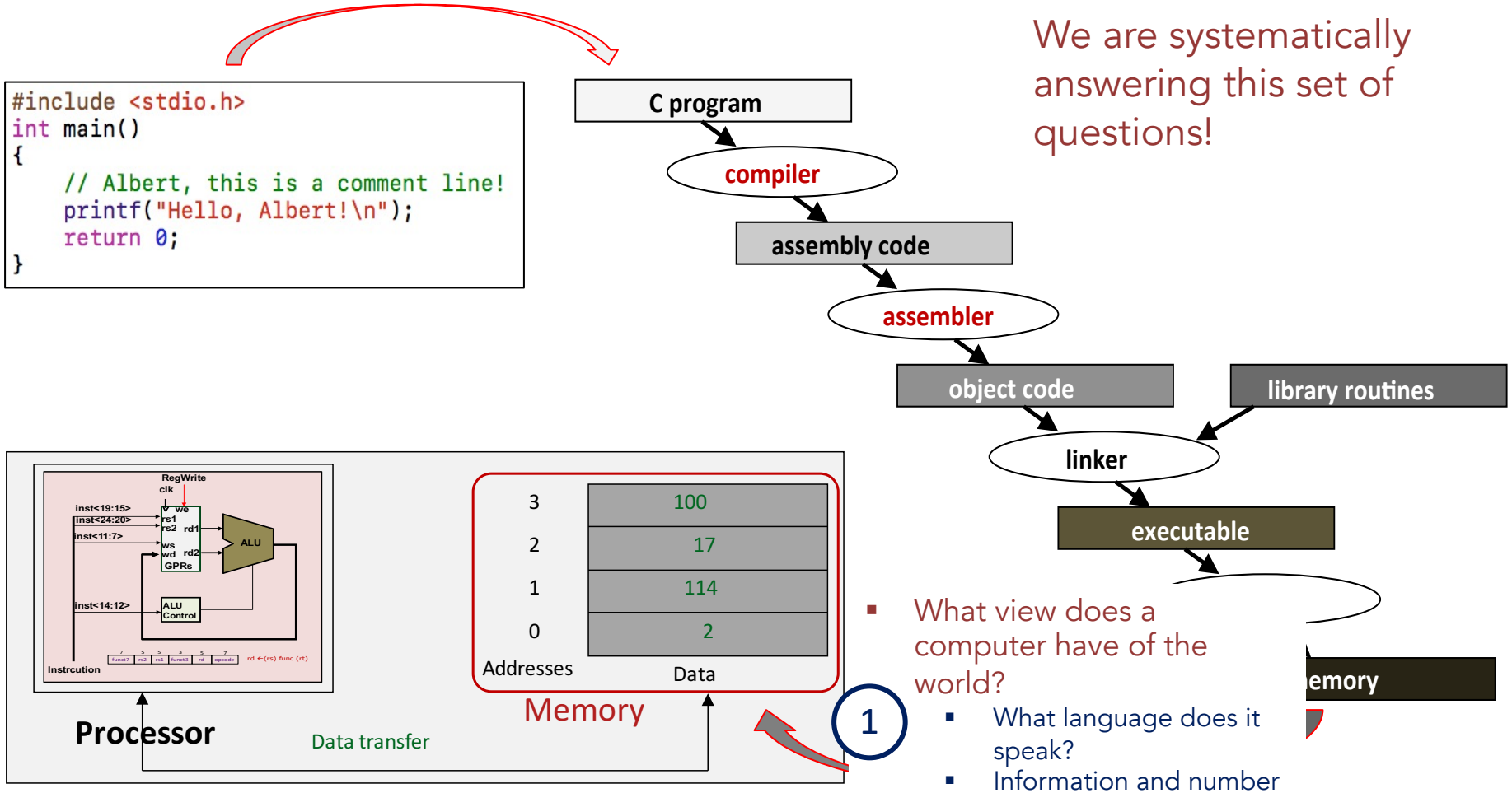
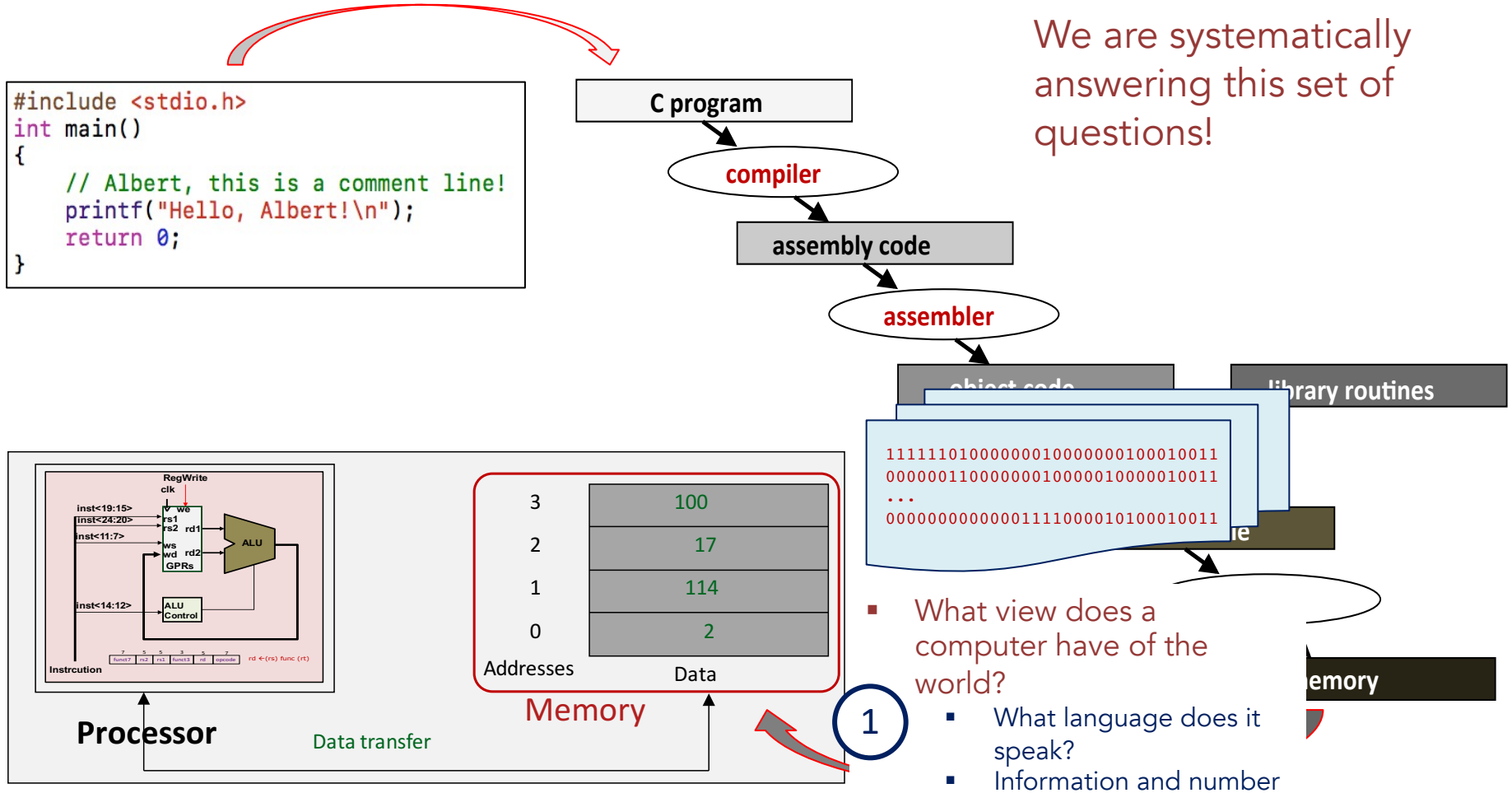


We are systematically answering this set of questions!

- What view does a computer have of the world?
  - What language does it speak?
  - Information and number representation

The Big Picture



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The Big Picture

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int main()
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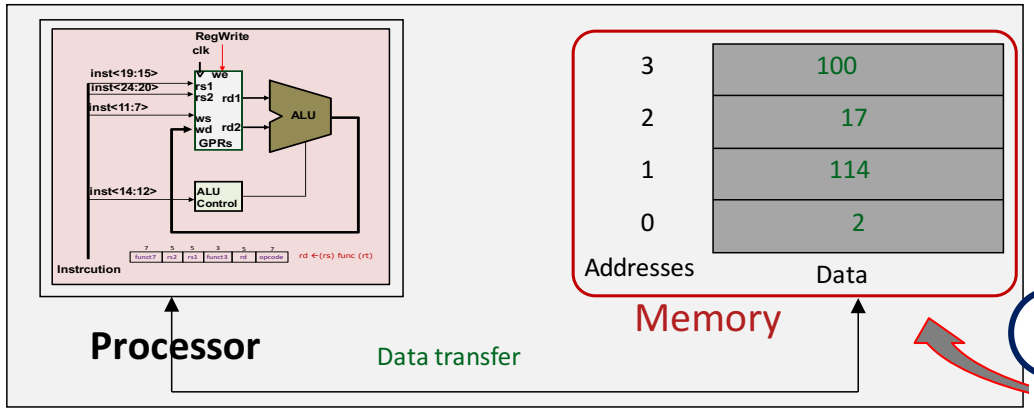
    return 0;
}
```

C program → compiler → assembly code → assembler → object code + library routines → linker → executable → memory

We are systematically answering this set of questions!

2

- How do we/users interact with the computer?
  - Computational problem solving
  - Expression through high-level languages



1

- What view does a computer have of the world?
  - What language does it speak?
  - Information and number representation

The Big Picture

```
#include <stdio.h>
int main()
{
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    printf("Hello, Albert!\n");
    return 0;
}
```

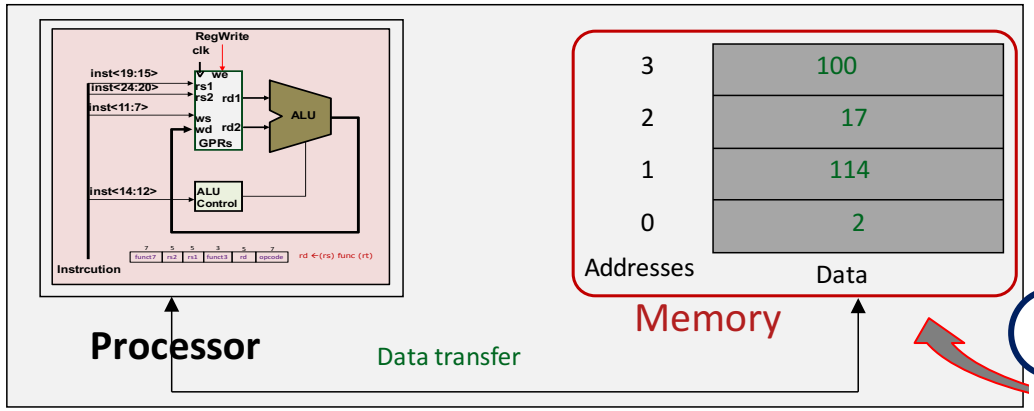
C program → compiler → assembly code → assembler → object code + library routines → linker → executable → memory

2

- How do we/users interact with the computer?
  - Computational problem solving
  - Expression through high-level languages

3

- How do we bridge these two computation expressions?
  - Compilation progress
  - ISA definition and format through RISC-V



1

- What view does a computer have of the world?
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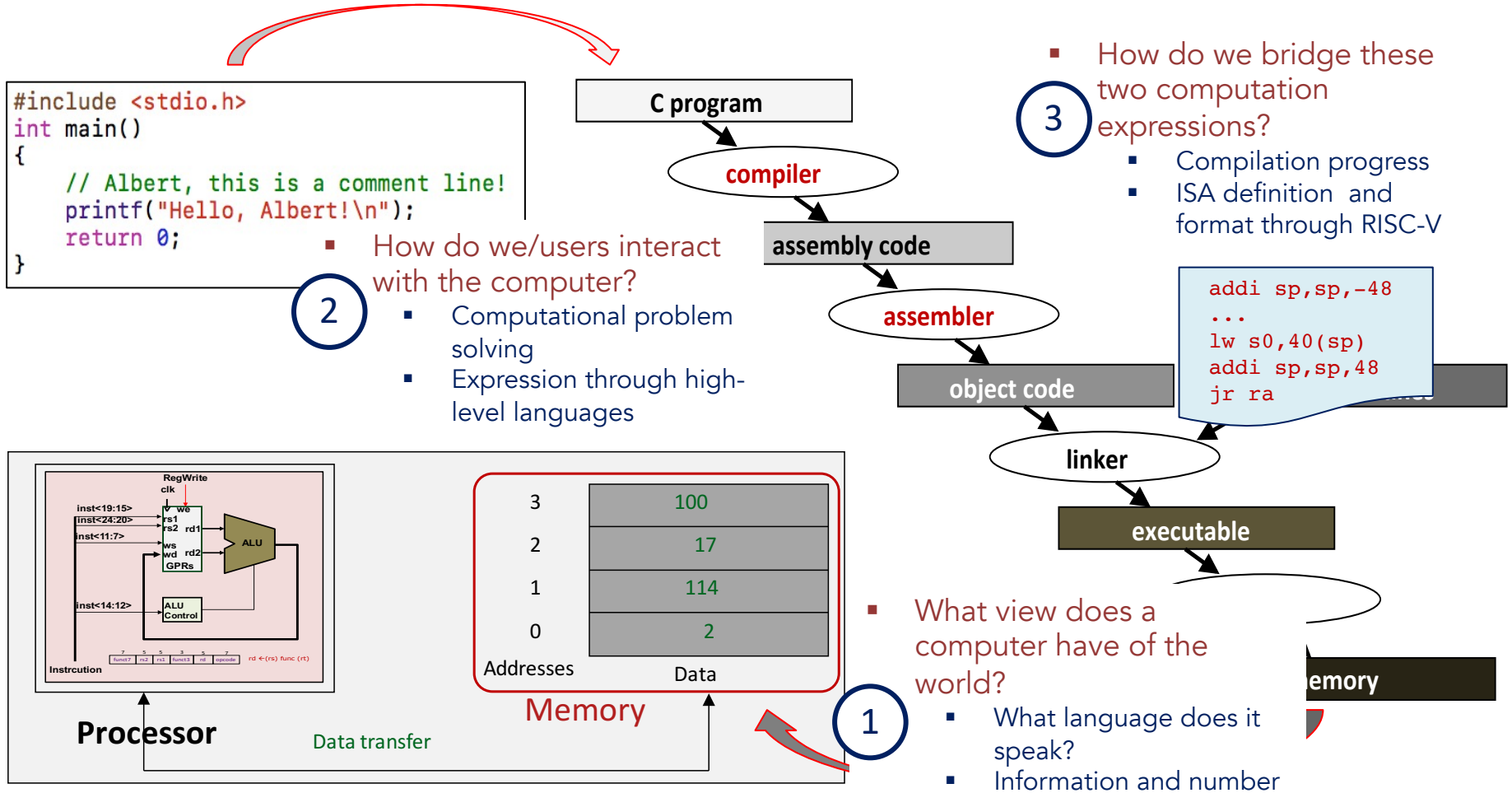
The Big Picture

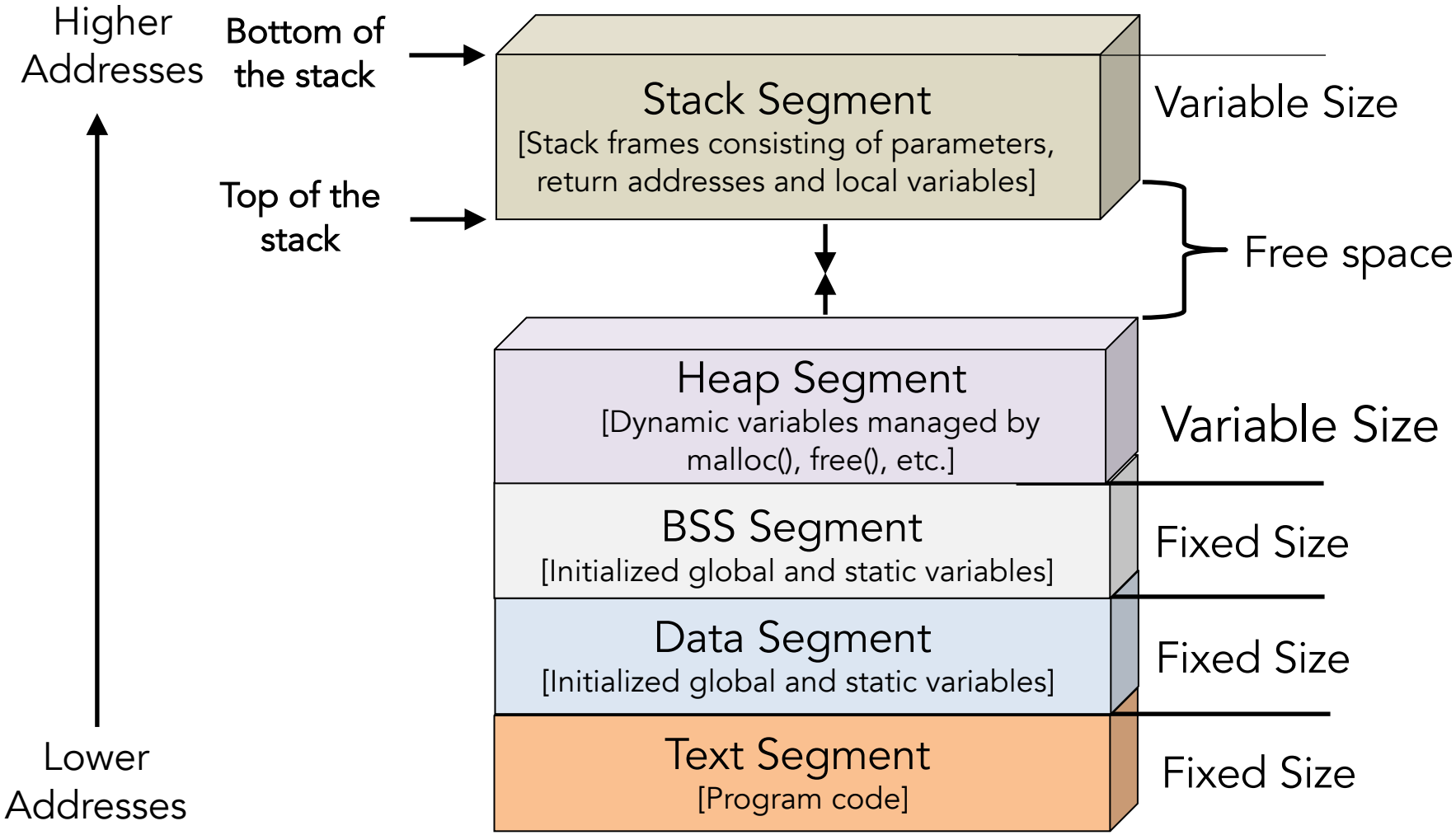


- How do we/users interact with the computer? (2)
  - Computational problem solving
  - Expression through high-level languages
- How do we bridge these two computation expressions? (3)
  - Compilation progress
  - ISA definition and format through RISC-V
- What view does a computer have of the world? (1)
  - What language does it speak?
  - Information and number representation

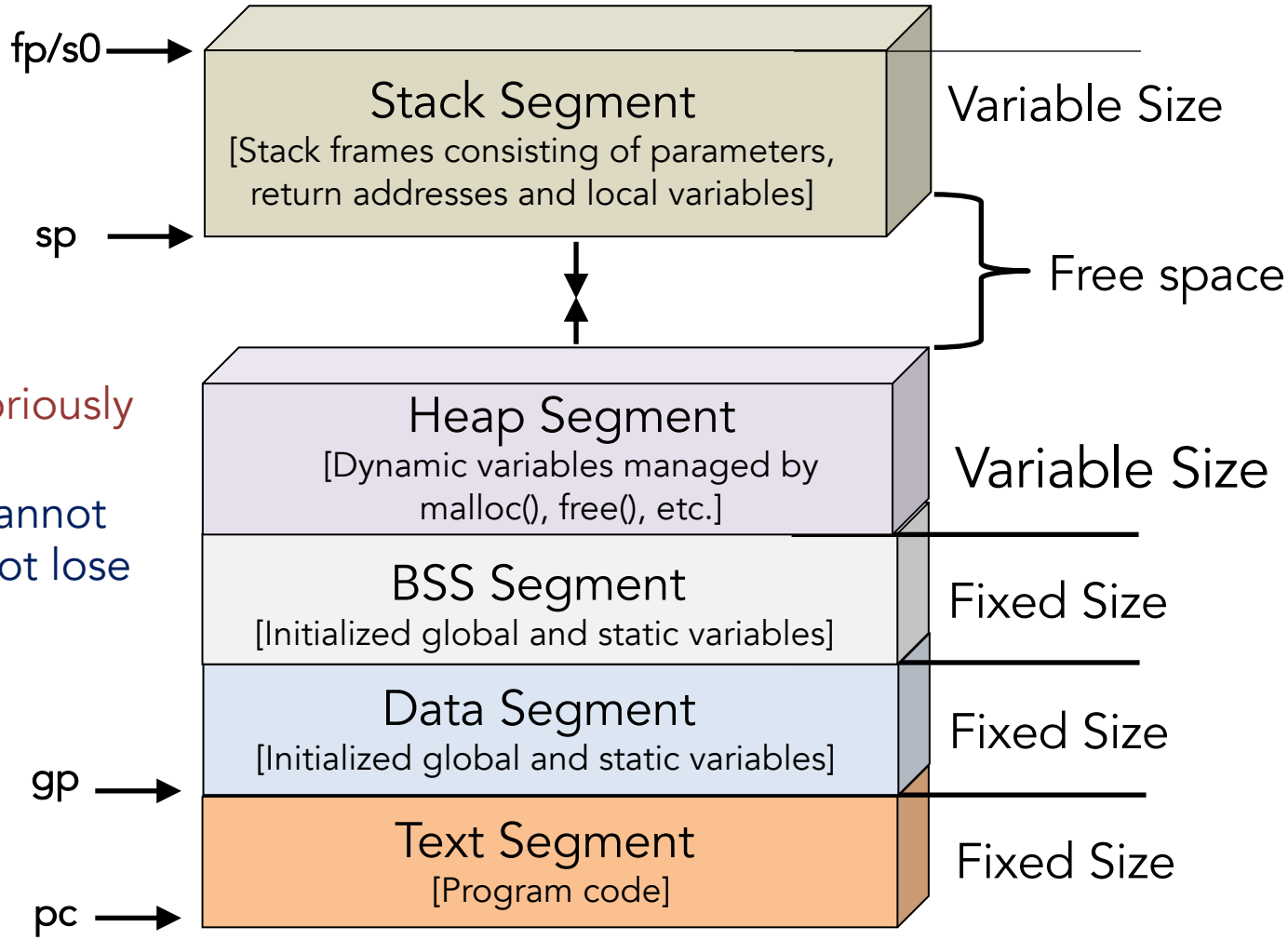
RISC-V ISA Registers

Name	Reg Number	Usage	Preserved across call?
zero	x0	The constant value 0	Yes
ra	x1	**Return address**	Yes
sp	x2	**Stack pointer**	Yes
gp	x3	Global pointer	Yes
tp	x4	Thread pointer	Yes
t0 – t2	x5 – x7	**Temporary registers**	No
s0/fp	x8	Frame pointer	Yes
s1	x9	Saved register	Yes
a0 - a1	x10 – x11	**Function arguments/Return values**	No
a2 – a7	x12 – x17	**Function arguments**	No

Program memory management



Program memory management



- And albert gloriously declares:
  - I simply cannot and will not lose myself!!!

RISC-V Assembly

```
int   val1  = 5;
int   val2;
int   val3  = 2;
int   val4[3] = {7,8,9};

char  string1[]  = "abc";
char  string2[3] = {'a','b','c'};

char  array1[5];
int   array2[2];
short int array3[3];


int foo (int num1, int num2, int num3, int
num4)
{
     int result;
     result = (num1 + num2) - (num3 + num4) ;
     return result;
}

void main(void) {
   array2 [0] = foo(val1, val2, val3, val4[1]);
}
```

```
val1:
     .word 5
val2:
     .zero 4
val3:
     .word 2
val4:
     .word 7
     .word 8
     .word 9
string1:
     .string "abc"
string2:
     .byte 97
     .byte 98
     .byte 99
array1:
     .zero 5
array2:
     .zero 8
array3:
     .zero 6
```

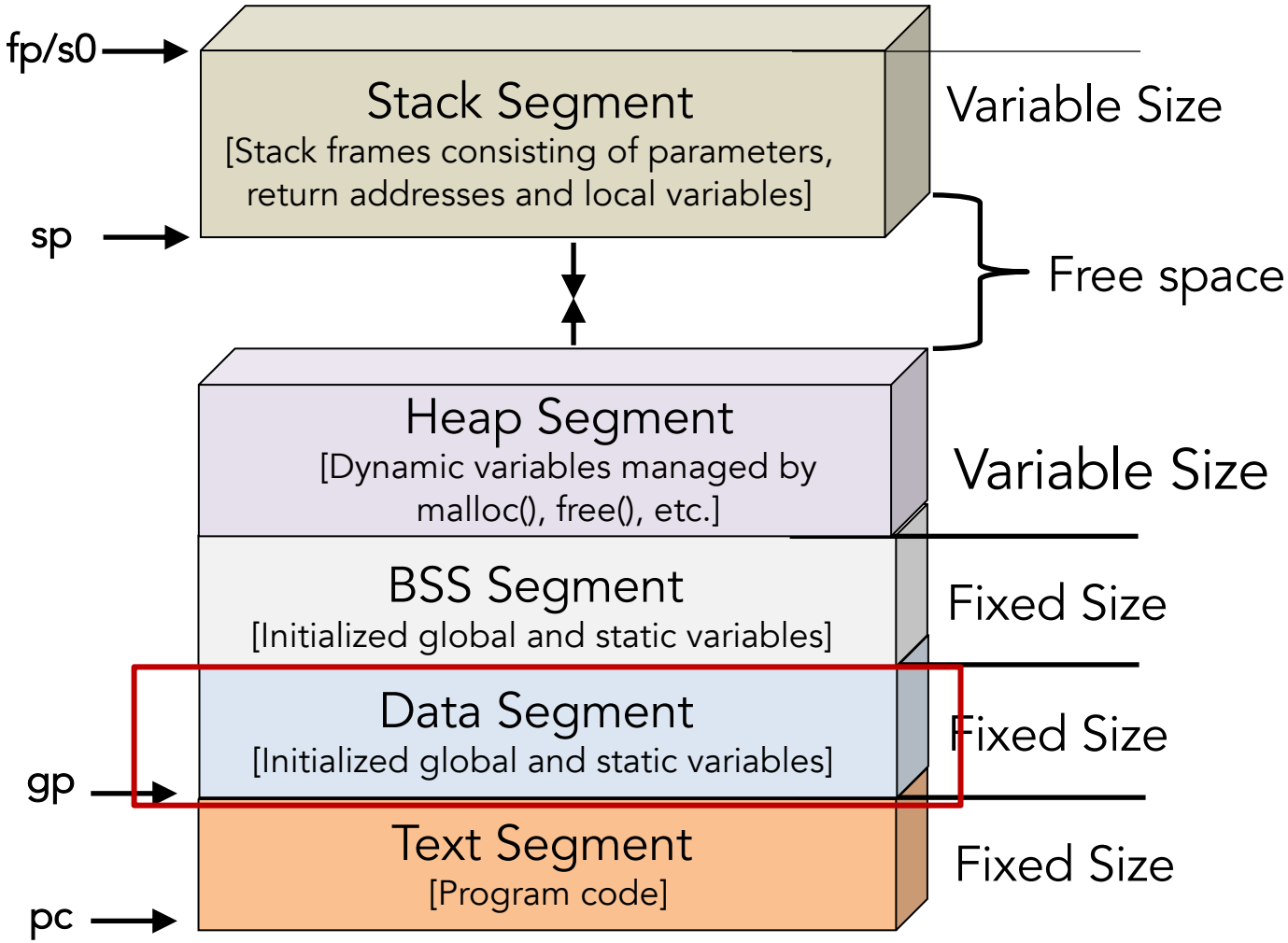
RISC-V Assembly

```
val1:
     .word 5
val2:
     .zero 4
val3:
     .word 2
val4:
     .word 7
     .word 8
     .word 9
string1:
     .string "abc"
string2:
     .byte 97
     .byte 98
     .byte 99
array1:
     .zero 5
array2:
     .zero 8
array3:
     .zero 6
```

Address	Value
0	5
1	0
2	0
3	0
4	?
5	?
6	?
7	?
8	2
9	0
A	0
B	0

Address	Value
C	7
D	0
E	0
F	0
10	8
11	0
12	0
13	0
14	9
15	0
16	0
17	0

Program memory management



RISC-V Assembly

```
val1:
     .word 5
val2:
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     .word 2
val4:
     .word 7
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string1:
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string2:
     .byte 97
     .byte 98
     .byte 99
array1:
     .zero 5
array2:
     .zero 8
array3:
     .zero 6
```

Address	Value
0	5
1	0
2	0
3	0
4	?
5	?
6	?
7	?
8	2
9	0
A	0
B	0

Address	Value
C	7
D	0
E	0
F	0
10	8
11	0
12	0
13	0
14	9
15	0
16	0
17	0

RISC-V Assembly

```
val1:
     .word 5
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val3:
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val4:
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string1:
     .string "abc"
string2:
     .byte 97
     .byte 98
     .byte 99
array1:
     .zero 5
array2:
     .zero 8
```

Program code addresses vs. hardware addresses

Address	Value
8000	5
8001	0
8002	0
8003	0
8004	?
8005	?
8006	?
8007	?
8008	2
8009	0
800A	0
800B	0

Address	Value
800C	7
800D	0
800E	0
800F	0
8010	8
8011	0
8012	0
8013	0
8014	9
8015	0
8016	0
8017	0

RISC-V Assembly

```
val1:
     .word 5
val2:
     .zero 4
val3:
     .word 2
val4:
     .word 7
     .word 8
     .word 9
string1:
     .string "abc"
string2:
     .byte 97
     .byte 98
     .byte 99
array1:
     .zero 5
array2:
     .zero 8
```

Program code addresses vs. hardware addresses

Address	Value
8018	0x61
8019	0x62
801A	0x63
801B	0
801C	0x61
801D	0x62
801E	0x63
801F	?
8020	?
8021	?
8022	?
8023	?

RISC-V Assembly – Let's Go All In

```
int   val1  = 5;
int   val2;
int   val3  = 2;
int   val4[3] = {7,8,9};

char  string1[]  = "abc";
char  string2[3] = {'a','b','c'};

char  array1[5];
int   array2[2];
short int array3[3];


int foo (int num1, int num2, int num3, int
num4)
{
     int result;
     result = (num1 + num2) - (num3 + num4) ;
     return result;
}

void main(void) {
   array2 [0] = foo(val1, val2, val3, val4[1]);
}
```

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     return result;
}

void main(void) {
   array2 [0] = foo(val1, val2, val3, val4[1]);
}
```

```
Note that: num1, num2, num3 and num4 are
a0, a1, a2, and a3, respectively.

foo:
add t0,a0,zero      # move num1 into t0
add t1,a1,zero      # move num2 into t1
add t2,a2,zero      # move num3 into t2

add t2,t2,a3        # t2 = num1 + num2

add t0,t0,t1        # t0 = num3 + num4

sub t1,t2,t0
# result = (num1 + num2) - (num3 + num4);

add a0,t1,zero
# result returned in a0
jr ra
```

RISC-V Assembly – Let's Go All In

```
int   val1  = 5;
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int foo (int num1, int num2, int num3, int
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{
     int result;
     result = (num1 + num2) - (num3 + num4) ;
     return result;
}

void main(void) {
   array2 [0] = foo(val1, val2, val3, val4[1]);
}
```

Silly Albert! Who are you kidding!

```
Note that: num1, num2, num3 and num4 are
a0, a1, a2, and a3, respectively.

foo:
add t0,a0,zero      # move num1 into t0
add t1,a1,zero      # move num2 into t1
add t2,a2,zero      # move num3 into t2

add t2,t2,a3        # t2 = num1 + num2

add t0,t0,t1        # t0 = num3 + num4

sub t1,t2,t0
# result = (num1 + num2) - (num3 + num4);

add a0,t1,zero
# result returned in a0
jr ra
```

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int foo (int num1, int num2, int num3, int
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{
     int result;
     result = (num1 + num2) - (num3 + num4) ;
     return result;
}

void main(void) {
   array2 [0] = foo(val1, val2, val3, val4[1]);
}
```

```
        .globl  val1
        .section .sdata,"aw",@progbits
        .align  2
        .type   val1, @object
        .size   val1, 4
val1:
        .word   5

        .globl  val2
        .section .sbss,"aw",@nobits
        .align  2
        .type   val2, @object
        .size   val2, 4
val2:
        .zero   4

        .globl  val3
        .section .sdata
        .align  2
        .type   val3, @object
        .size   val3, 4
val3:
        .word   2
```

RISC-V Assembly – Let's Go All In

```
int   val1  = 5;
int   val2;
int   val3  = 2;
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}

void main(void) {
   array2 [0] = foo(val1, val2, val3, val4[1]);
}
```

```
        .globl  val1
        .section .sdata,"aw",@progbits
        .align  2
        .type   val1, @object
        .size   val1, 4
val1:
        .word   5

        .globl  val2
        .section .sbss,"aw",@nobits
        .align  2
        .type   val2, @object
        .size   val2, 4
val2:
        .zero   4

        .globl  val3
        .section .sdata
        .align  2
        .type   val3, @object
        .size   val3, 4
val3:
        .word   2
```

RISC-V Assembly – Let's Go All In

```
int   val1  = 5;
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int   val4[3] = {7,8,9};

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int   array2[2];
short int array3[3];


int foo (int num1, int num2, int num3, int
num4)
{
     int result;
     result = (num1 + num2) - (num3 + num4) ;
     return result;
}

void main(void) {
   array2 [0] = foo(val1, val2, val3, val4[1]);
}
```

```
        .globl  val4
        .data
        .align  2
        .type   val4, @object
        .size   val4, 12
val4:
        .word   7
        .word   8
        .word   9

        .globl  string1
        .section        .sdata
        .align  2
        .type   string1, @object
        .size   string1, 4
string1:
        .string "abc"

        .globl  string2
        .align  2
        .type   string2, @object
        .size   string2, 3
string2:
        .byte   97
        .byte   98
        .byte   99
```

RISC-V Assembly – Let's Go All In

```
int   val1  = 5;
int   val2;
int   val3  = 2;
int   val4[3] = {7,8,9};

char  string1[]  = "abc";
char  string2[3] = {'a','b','c'};

char  array1[5];
int   array2[2];
short int array3[3];


int foo (int num1, int num2, int num3, int
num4)
{
     int result;
     result = (num1 + num2) - (num3 + num4) ;
     return result;
}

void main(void) {
   array2 [0] = foo(val1, val2, val3, val4[1]);
}
```

```
        .globl  val4
        .data
        .align  2
        .type   val4, @object
        .size   val4, 12
val4:
        .word   7
        .word   8
        .word   9

        .globl  string1
        .section        .sdata
        .align  2
        .type   string1, @object
        .size   string1, 4
string1:
        .string "abc"

        .globl  string2
        .align  2
        .type   string2, @object
        .size   string2, 3
string2:
        .byte   97
        .byte   98
        .byte   99
```

RISC-V Assembly – Let's Go All In

```
int   val1  = 5;
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int foo (int num1, int num2, int num3, int
num4)
{
     int result;
     result = (num1 + num2) - (num3 + num4) ;
     return result;
}

void main(void) {
   array2 [0] = foo(val1, val2, val3, val4[1]);
}
```

```
        .globl  array1
        .section        .sbss
        .align  2
        .type   array1, @object
        .size   array1, 5
array1:
        .zero   5


        .globl  array2
        .section        .sbss
        .align  2
        .type   array2, @object
        .size   array2, 8
array2:
        .zero   8


        .globl  array3
        .section        .sbss
        .align  2
        .type   array3, @object
        .size   array3, 6
array3:
        .zero   6
```

RISC-V Assembly – Let's Go All In

```
int   val1  = 5;
int   val2;
int   val3  = 2;
int   val4[3] = {7,8,9};

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int foo (int num1, int num2, int num3, int
num4)
{
     int result;
     result = (num1 + num2) - (num3 + num4) ;
     return result;
}

void main(void) {
   array2 [0] = foo(val1, val2, val3, val4[1]);
}
```

```
        .text
        .align  1
        .globl  foo
        .type   foo, @function
foo:
        addi    sp,sp,-48
        sw      s0,44(sp)
        addi    s0,sp,48
        sw      a0,-36(s0)
        sw      a1,-40(s0)
        sw      a2,-44(s0)
        sw      a3,-48(s0)
        lw      a4,-36(s0)
        lw      a5,-40(s0)
        add     a4,a4,a5
        lw      a3,-44(s0)
        lw      a5,-48(s0)
        add     a5,a3,a5
        sub     a5,a4,a5
        sw      a5,-20(s0)
        lw      a5,-20(s0)
        mv      a0,a5
        lw      s0,44(sp)
        addi    sp,sp,48
        jr      ra
```

RISC-V Assembly – Let's Go All In

```
int   val1  = 5;
int   val2;
int   val3  = 2;
int   val4[3] = {7,8,9};

char  string1[]  = "abc";
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char  array1[5];
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int foo (int num1, int num2, int num3, int
num4)
{
     int result;
     result = (num1 + num2) - (num3 + num4) ;
     return result;
}

void main(void) {
   array2 [0] = foo(val1, val2, val3, val4[1]);
}
```

- Stack pointer adjustment

```
        .text
        .align  1
        .globl  foo
        .type   foo, @function
foo:
        addi    sp,sp,-48        (1)
        sw      s0,44(sp)
        addi    s0,sp,48
        sw      a0,-36(s0)
        sw      a1,-40(s0)
        sw      a2,-44(s0)
        sw      a3,-48(s0)
        lw      a4,-36(s0)
        lw      a5,-40(s0)
        add     a4,a4,a5
        lw      a3,-44(s0)
        lw      a5,-48(s0)
        add     a5,a3,a5
        sub     a5,a4,a5
        sw      a5,-20(s0)
        lw      a5,-20(s0)
        mv      a0,a5
        lw      s0,44(sp)
        addi    sp,sp,48
        jr      ra
```

RISC-V Assembly – Let's Go All In

```
int   val1  = 5;
int   val2;
int   val3  = 2;
int   val4[3] = {7,8,9};

char  string1[]  = "abc";
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char  array1[5];
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int foo (int num1, int num2, int num3, int
num4)
{
     int result;
     result = (num1 + num2) - (num3 + num4) ;
     return result;
}

void main(void) {
   array2 [0] = foo(val1, val2, val3, val4[1]);
}
```

- Save old frame pointer
  - Caller's frame pointer

```
        .text
        .align  1
        .globl  foo
        .type   foo, @function
foo:
        addi    sp,sp,-48
        sw      s0,44(sp)
        addi    s0,sp,48
        sw      a0,-36(s0)
        sw      a1,-40(s0)
        sw      a2,-44(s0)
        sw      a3,-48(s0)
        lw      a4,-36(s0)
        lw      a5,-40(s0)
        add     a4,a4,a5
        lw      a3,-44(s0)
        lw      a5,-48(s0)
        add     a5,a3,a5
        sub     a5,a4,a5
        sw      a5,-20(s0)
        lw      a5,-20(s0)
        mv      a0,a5
        lw      s0,44(sp)
        addi    sp,sp,48
        jr      ra
```

2

RISC-V Assembly – Let's Go All In

```
int   val1  = 5;
int   val2;
int   val3  = 2;
int   val4[3] = {7,8,9};

char  string1[
char  string2[

char  array1[5
int   array2[2
short int arra

int foo (int n
num4)
{
     int result;
     result = (num1 + num2) - (num3 + num4) ;
     return result;
}

void main(void) {
   array2 [0] = foo(val1, val2, val3, val4[1]);
}
```

- The frame pointer (fp/s0) points to the start of the stack frame
  - It points to the base of the stack frame
  - Parameters passed in to the subroutine remain at constant places relative to the frame pointer
- It does not move for the duration of the subroutine call

```
        .text
        .align  1
        .globl  foo
        .type   foo, @function
foo:
        addi    sp,sp,-48
        sw      s0,44(sp)
        addi    s0,sp,48
        sw      a0,-36(s0)
        sw      a1,-40(s0)
        sw      a2,-44(s0)
        sw      a3,-48(s0)
        lw      a4,-36(s0)
        lw      a5,-40(s0)
        add     a4,a4,a5
        lw      a3,-44(s0)
        lw      a5,-48(s0)
        add     a5,a3,a5
        sub     a5,a4,a5
        sw      a5,-20(s0)
        lw      a5,-20(s0)
        mv      a0,a5
        lw      s0,44(sp)
        addi    sp,sp,48
        jr      ra
```

3

RISC-V Assembly – Let's Go All In

```
int   val1  = 5;
int   val2;
int   val3  = 2;
int   val4[3] = {7,8,9};

char  string1[]  = "abc";
char  string2[3] = {'a','

char  array1[5];
int   array2[2];
short int array3[3];


int foo (int num1, int nu
num4)
{
     int result;
     result = (num1 + num2) - (num3 + num4) ;
     return result;
}

void main(void) {
   array2 [0] = foo(val1, val2, val3, val4[1]);
}
```

- Save the function arguments
  - In case, something happens in the middle of the function execution
    - Like divide by zero

```
        .text
        .align  1
        .globl  foo
        .type   foo, @function
foo:
        addi    sp,sp,-48
        sw      s0,44(sp)
        addi    s0,sp,48
        sw      a0,-36(s0)
        sw      a1,-40(s0)
        sw      a2,-44(s0)
        sw      a3,-48(s0)
        lw      a4,-36(s0)
        lw      a5,-40(s0)
        add     a4,a4,a5
        lw      a3,-44(s0)
        lw      a5,-48(s0)
        add     a5,a3,a5
        sub     a5,a4,a5
        sw      a5,-20(s0)
        lw      a5,-20(s0)
        mv      a0,a5
        lw      s0,44(sp)
        addi    sp,sp,48
        jr      ra
```

4

RISC-V Assembly – Let's Go All In

```
int   val1  = 5;
int   val2;
int   val3  = 2;
int   val4[3] = {7,8,9};

char  string1[]  = "abc";
char  string2[3] = {'a','

char  array1[5];
int   array2[2];
short int array3[3];


int foo (int num1, int num2, int num3, int
num4)
{
     int result;
     result = (num1 + num2) - (num3 + num4) ;
     return result;
}

void main(void) {
   array2 [0] = foo(val1, val2, val3, val4[1]);
}
```

- Perform actual operations

```
        .text
        .align  1
        .globl  foo
        .type   foo, @function
foo:
        addi    sp,sp,-48
        sw      s0,44(sp)
        addi    s0,sp,48
        sw      a0,-36(s0)
        sw      a1,-40(s0)
        sw      a2,-44(s0)
        sw      a3,-48(s0)
        lw      a4,-36(s0)
        lw      a5,-40(s0)
        add     a4,a4,a5
        lw      a3,-44(s0)
        lw      a5,-48(s0)
        add     a5,a3,a5
        sub     a5,a4,a5
        sw      a5,-20(s0)
        lw      a5,-20(s0)
        mv      a0,a5
        lw      s0,44(sp)
        addi    sp,sp,48
        jr      ra
```

5

RISC-V Assembly – Let's Go All In

```
int   val1  = 5;
int   val2;
int   val3  = 2;
int   val4[3] = {7,8,9};

char  string1[]  = "abc";
char  string2[3] = {'a','b','c'};

char  array1[5];
int   array2[2];
short int array3[3];


int foo (int num1, int num2, int num3, int
num4)
{
     int result;
     result = (num1 + num2) - (num3 + num4) ;
     return result;
}

void main(void) {
   array2 [0] = foo(val1, val2, val3, val4[1]);
}
```

- Return result

```
        .text
        .align  1
        .globl  foo
        .type   foo, @function
foo:
        addi    sp,sp,-48
        sw      s0,44(sp)
        addi    s0,sp,48
        sw      a0,-36(s0)
        sw      a1,-40(s0)
        sw      a2,-44(s0)
        sw      a3,-48(s0)
        lw      a4,-36(s0)
        lw      a5,-40(s0)
        add     a4,a4,a5
        lw      a3,-44(s0)
        lw      a5,-48(s0)
        add     a5,a3,a5
        sub     a5,a4,a5
        sw      a5,-20(s0)
        lw      a5,-20(s0)
        mv      a0,a5
        lw      s0,44(sp)
        addi    sp,sp,48
        jr      ra
```

6

RISC-V Assembly – Let's Go All In

```
int   val1  = 5;
int   val2;
int   val3  = 2;
int   val4[3] = {7,8,9};

char  string1[]  = "abc";
char  string2[3] = {'a','b','c'};

char  array1[5];
int   array2[2];
short int array3[3];


int foo (int num1, int num2, int num3, int
num4)
{
     int result;
     result = (num1 + num2) - (num3 + num4) ;
     return result;
}

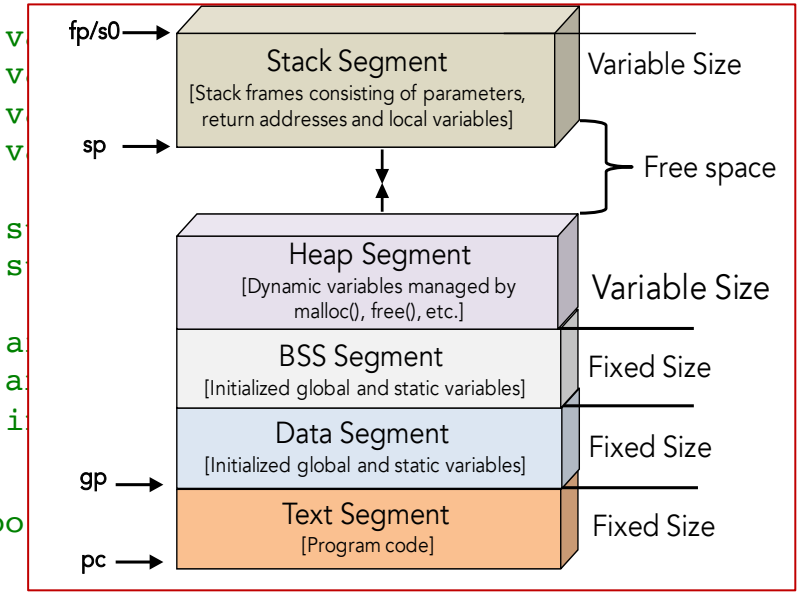
void main(void) {
   array2 [0] = foo(val1,
}
```

- Rollback things (frame pointer and stack pointer)

```
        .text
        .align  1
        .globl  foo
        .type   foo, @function
foo:
        addi    sp,sp,-48
        sw      s0,44(sp)
        addi    s0,sp,48
        sw      a0,-36(s0)
        sw      a1,-40(s0)
        sw      a2,-44(s0)
        sw      a3,-48(s0)
        lw      a4,-36(s0)
        lw      a5,-40(s0)
        add     a4,a4,a5
        lw      a3,-44(s0)
        lw      a5,-48(s0)
        add     a5,a3,a5
        sub     a5,a4,a5
        sw      a5,-20(s0)
        lw      a5,-20(s0)
        mv      a0,a5
        lw      s0,44(sp)
        addi    sp,sp,48
        jr      ra
```

7

RISC-V Assembly – Let's Go All In



- The frame pointer (fp/s0) points to the start of the stack frame
  - It points to the base of the stack frame
  - It is restored at the end of the call to its previous value

```
        .text
        .align  1
        .globl  foo
        .type   foo, @function
foo:
        addi    sp,sp,-48
        sw      s0,44(sp)
        addi    s0,sp,48
        sw      a0,-36(s0)
        sw      a1,-40(s0)
        sw      a2,-44(s0)
        sw      a3,-48(s0)
        lw      a4,-36(s0)
        lw      a5,-40(s0)
        add     a4,a4,a5
        lw      a3,-44(s0)
        lw      a5,-48(s0)
        add     a5,a3,a5
        sub     a5,a4,a5
        sw      a5,-20(s0)
        lw      a5,-20(s0)
        mv      a0,a5
        lw      s0,44(sp)
        addi    sp,sp,48
        jr      ra
```

7

RISC-V Assembly – Let's Go All In

```
int   val1  = 5;
int   val2;
int   val3  = 2;
int   val4[3] = {7,8,9};

char  string1[]  = "abc";
char  string2[3] = {'a','b','c'};

char  array1[5];
int   array2[2];
short int array3[3];


int foo (int num1, int num2, int num3, int
num4)
{
     int result;
     result = (num1 + num2) - (num3 + num4) ;
     return result;
}

void main(void) {
   array2 [0] = foo(val1, val2, val3, val4[1]);
}
```

```
        .text
        .align  1
        .globl  foo
        .type   foo, @function
foo:
        addi    sp,sp,-48
        sw      s0,44(sp)
        addi    s0,sp,48
        sw      a0,-36(s0)
        sw      a1,-40(s0)
        sw      a2,-44(s0)
        sw      a3,-48(s0)
        lw      a4,-36(s0)
        lw      a5,-40(s0)
        add     a4,a4,a5
        lw      a3,-44(s0)
        lw      a5,-48(s0)
        add     a5,a3,a5
        sub     a5,a4,a5
        sw      a5,-20(s0)
        lw      a5,-20(s0)
        mv      a0,a5
        lw      s0,44(sp)
        addi    sp,sp,48
        jr      ra
```

8

- Jump out and time to go Albert!

RISC-V Assembly – Let's Go All In

```
int   val1  = 5;
int   val2;
int   val3  = 2;
int   val4[3] = {7,8,9};

char  string1[]  = "abc";
char  string2[3] = {'a','b','c'};

char  array1[5];
int   array2[2];
short int array3[3];


int foo (int num1, int num2, int num3, int
num4)
{
     int result;
     result = (num1 + num2) - (num3 + num4) ;
     return result;
}

void main(void) {
   array2 [0] = foo(val1, val2, val3, val4[1]);
}
```

```
        .text
        .align  1
        .globl  foo
        .type   foo, @function
foo:
        addi    sp,sp,-48
        sw      s0,44(sp)
        addi    s0,sp,48
        sw      a0,-36(s0)
        sw      a1,-40(s0)
        sw      a2,-44(s0)
        sw      a3,-48(s0)
        lw      a4,-36(s0)
        lw      a5,-40(s0)
        add     a4,a4,a5
        lw      a3,-44(s0)
        lw      a5,-48(s0)
        add     a5,a3,a5
        sub     a5,a4,a5
        sw      a5,-20(s0)
        lw      a5,-20(s0)
        mv      a0,a5
        lw      s0,44(sp)
        addi    sp,sp,48
        jr      ra
```

8

- Jump out and time to go Albert!

RISC-V Assembly – Let's Go All In

```
int   val1  = 5;
int   val2;
int   val3  = 2;
int   val4[3] = {7,8,9};

char  string1[]  = "abc";
char  string2[3] = {'a','b','c'};

char  array1[5];
int   array2[2];
short int array3[3];


int foo (int num1, int num2, int num3, int
num4)
{
     int result;
     result = (num1 + num2) - (num3 + num4) ;
     return result;
}

void main(void) {
   array2 [0] = foo(val1, val2, val3, val4[1]);
}
```

```
        .zero   6
        .text
        .align  1
        .globl  main
        .type   main, @function
main:
        addi    sp,sp,-16
        sw      ra,12(sp)
        sw      s0,8(sp)
        addi    s0,sp,16
        lui     a5,%hi(val1)
        lw      a4,%lo(val1)(a5)
        lui     a5,%hi(val2)
        lw      a1,%lo(val2)(a5)
        lui     a5,%hi(val3)
        lw      a2,%lo(val3)(a5)
        lui     a5,%hi(val4)
        addi    a5,a5,%lo(val4)
        lw      a5,4(a5)
        mv      a3,a5
        mv      a0,a4
        call    foo
        mv      a4,a0
        lui     a5,%hi(array2)
        sw      a4,%lo(array2)(a5)
        li      a5,0
        mv      a0,a5
        lw      ra,12(sp)
        lw      s0,8(sp)
        addi    sp,sp,16
        jr      ra
```

RISC-V Assembly – Let's Go All In

```
int   val1  = 5;
int   val2;
int   val3  = 2;
int   val4[3] = {7,8,9};

char  string1[]  = "abc";
char  string2[3] = {'a','b','c'};

char  array1[5];
int   array2[2];
short int array3[3];


int foo (int num1, int num2, int num3, int
num4)
{
     int result;
     result = (num1 + num2) - (num3 + num4) ;
     return result;
}

void main(void) {
   array2 [0] = foo(val1, val2, val3, val4[1]);
}
```

```
        .zero   6
        .text
        .align  1
        .globl  main
        .type   main, @function
main:
        addi    sp,sp,-16
        sw      ra,12(sp)
        sw      s0,8(sp)
        addi    s0,sp,16
        lui     a5,%hi(val1)
        lw      a4,%lo(val1)(a5)
        lui     a5,%hi(val2)
        lw      a1,%lo(val2)(a5)
        lui     a5,%hi(val3)
        lw      a2,%lo(val3)(a5)
        lui     a5,%hi(val4)
        addi    a5,a5,%lo(val4)
        lw      a5,4(a5)
        mv      a3,a5
        mv      a0,a4
        call    foo
        mv      a4,a0
        lui     a5,%hi(array2)
        sw      a4,%lo(array2)(a5)
        li      a5,0
        mv      a0,a5
        lw      ra,12(sp)
        lw      s0,8(sp)
        addi    sp,sp,16
        jr      ra
```

Pseudo Instructions

Useful Pseudo-instructions	Meaning	Actual Translation
mv rd, rs	Copy register rs to rd	addi rd, rs, 0
li rd, immediate	Load immediate into rd	addi rd, $0, immed
beqz rs, offset *bnez rs, offset* *bgtz rs, offset*	Branch if = zero Branch if != zero Branch if > zero	beq rs, x0, offset bne rs, x0, offset blt x0, rs, offset
j offset *jal offset* *jr rs* *jalr rs*	Jump Jump and link Jump register Jump and link register	jal x0, offset jal x1, offset jalr x0, rs, 0 jalr x1, rs, 0
call offset	Call far-away subroutine	auipc x6, offset[31:12] jalr x1, x6, offset[11:0]
ret	Return from subroutine	jalr x0, x1, 0
nop	Do nothing useful	add x0, x0, x0

Function Entry

```
prolog:
    addi    sp, sp, -16   # -16 (frame size) depends on the amount of space needed
    sw      ra, 12(sp)    # offset must be framesize-4
    sw      fp, 8(sp)     # store the caller's fp
    sw      gp, 4(sp)     # store caller's gp
    mv      fp, sp        # fp is now the new function's frame base pointer


# …
# The actual functional body of the function
# …

epilog:
    lw      gp, 4(sp)
    lw      fp, 8(sp)
    addi    sp, sp, 16     # reverse the effect of first instruction
    jr      ra
```

Assembly Programs

- If (condition) then do this

```
if ( i == j )
    i++ ;
j++;
```

```
Assuming t1 stores i and t2 stores j:

       bne  t1, t2, NEXT   # branch if !( i == j )
       addi t1, t1, 1      # i++
NEXT:  addi t2, t2, 1      # j++
```

Assembly Programs

- If (condition) then do this else do that

```
if ( i == j && i == k )

    i++ ;
else
    j++;

j = i + k ;
```

```
Assuming t0 stores i, t1 stores j, and t2 stores k:

      bne  t0, t1, ELSE  # cond1: branch if !( i == j )
      bne  t0, t2, ELSE  # cond2: branch if !( i == k )
      addi t0, t0, 1     # if-body: i++
      j NEXT             # jump over else
ELSE: addi t1, t1, 1     # else-body: j++
NEXT: add  t1, t0, t2    # j = i + k
```

Assembly Programs

- While (condition) then keep doing this

```
while ( i < j )
{
    k = k * 2;
    i++;
}
```

```
Assuming t0 stores i, t1 stores j, and t2 stores k:

Loop: bge  t0, t1, DONE # branch if ! ( i < j )
      add  t2, t2, t2   # k = k * 2
      addi t0, t0, 1    # i++
      j Loop            # jump back to top of loop
DONE:
```

Assembly Programs

- For (these many times) do this

```
for (i = 0;  i < j; i++)
{
    k = k * 2;
}
```

```
Assuming t0 stores i, t1 stores j, and t2 stores k:

      addi t0, $0, 0      # i = 0
Loop: bge  t0, t1, DONE   # branch if ! ( i < j )
      add  t2, t2, t2     # k = k * 2
      addi t0, t0, 1      # i++
      j Loop              # jump back to top of loop
DONE:
```

Assembly Programs

- For (these many times) do this

```
switch( i ) {
    case 1:
        i++ ;
    break;
    case 2:
        i += 2 ;
    break;
    case 3:
        i += 3 ;
    break;
}
```

```
Assuming t0 stores i and t1 stores temp:

      addi t1, zero, 1     # case 1: set temp to 1
      bne  t0, t1, CASE2   # false: branch to case 2
      j CASE1_BODY         # true: branch to case 1 body
CASE2:
      addi t1, zero, 2     # case 2: set temp to 2
      bne  t0, t1, CASE3   # false: branch to case 3
      j CASE2_BODY         # true: branch to case 2 body
CASE3:
      addi t1, zero, 3     # case 3: set temp to 3
      bne  t0, t1, EXIT    # false: branch to exit
      j CASE3_BODY         # true: branch to case 3 body
CASE1_BODY:
      addi t0, t0, 1       # case 1 body: i++
      j EXIT               # break
CASE2_BODY:
      addi t0, t0, 2       # case 2 body: i += 2
      j EXIT               # break
CASE3_BODY:
      addi t0, t0, 3       # case 3 body: i += 3
      j EXIT               # break
EXIT:
```

Assembly Programs

- Short program

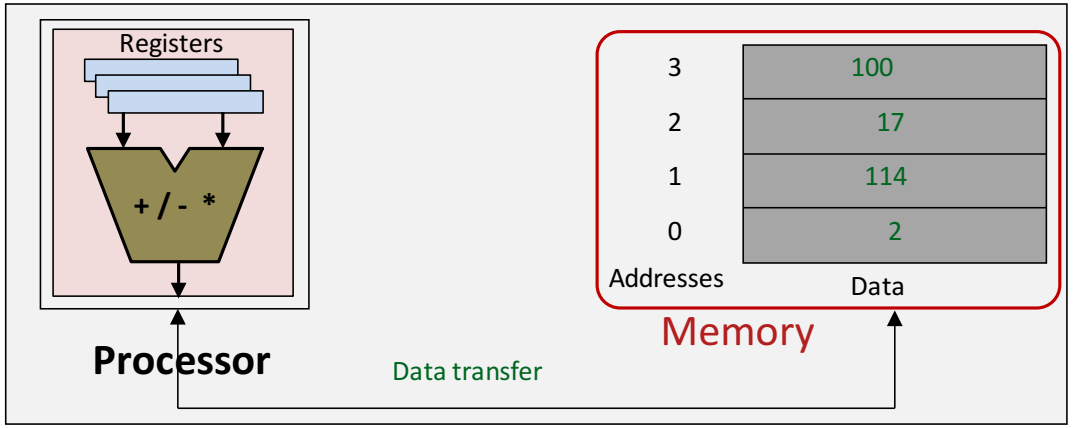
```
clear(int array[], int size)
{
  int i;
  for (i = 0; i < size; i += 1)
    array[i] = 0;
}
```

```
        mv   t0,zero       # i = 0

Loop:   sll t1,t0,2        # t1 = i * 4
        add t2,a0,t1       # t2 = &array[i]
        sw zero, 0(t2)     # array[i] = 0
        addi t0,t0,1       # i = i + 1
        slt a3,t0,a1       # a3 = (i < size)
        bne a3,zero,Loop   # if (…)
                           # goto loop
```

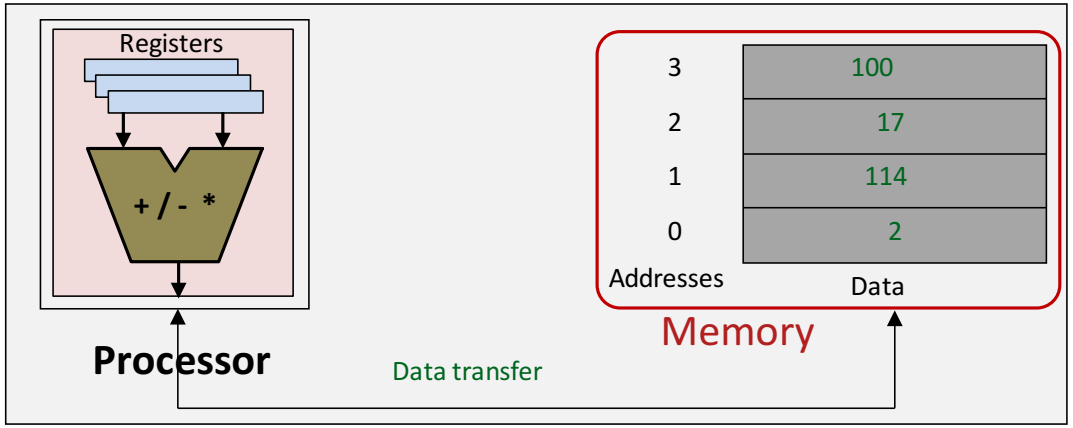
Data Addressing Modes

- RISC-V has four data addressing modes
  1. Register
     - Data is in a register
  2. Immediate
     - Data is specified in the instruction directly
  3. Displacement
     - Data is in memory with address calculated as Base + Offset
  4. PC-Relative
     - Data is in memory with address calculated as PC + Offset



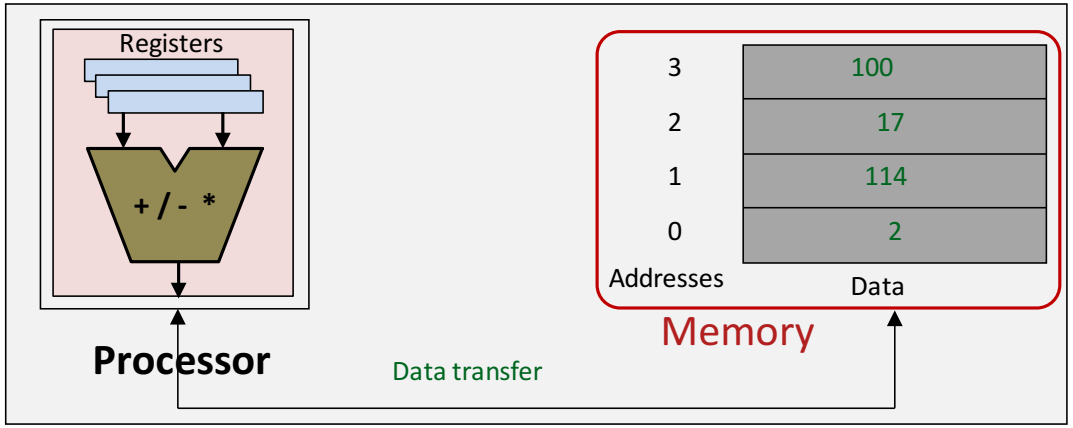
Data Addressing Modes

- RISC-V has four data addressing modes
  - Memory related addressing modes
    - Register indirect
      - add x2, (x1)
      - x1 ← x2+Mem[x1]
    - Displacement
      - add x2, 64(x1)
      - x1 ← x2+Mem[64+x1]

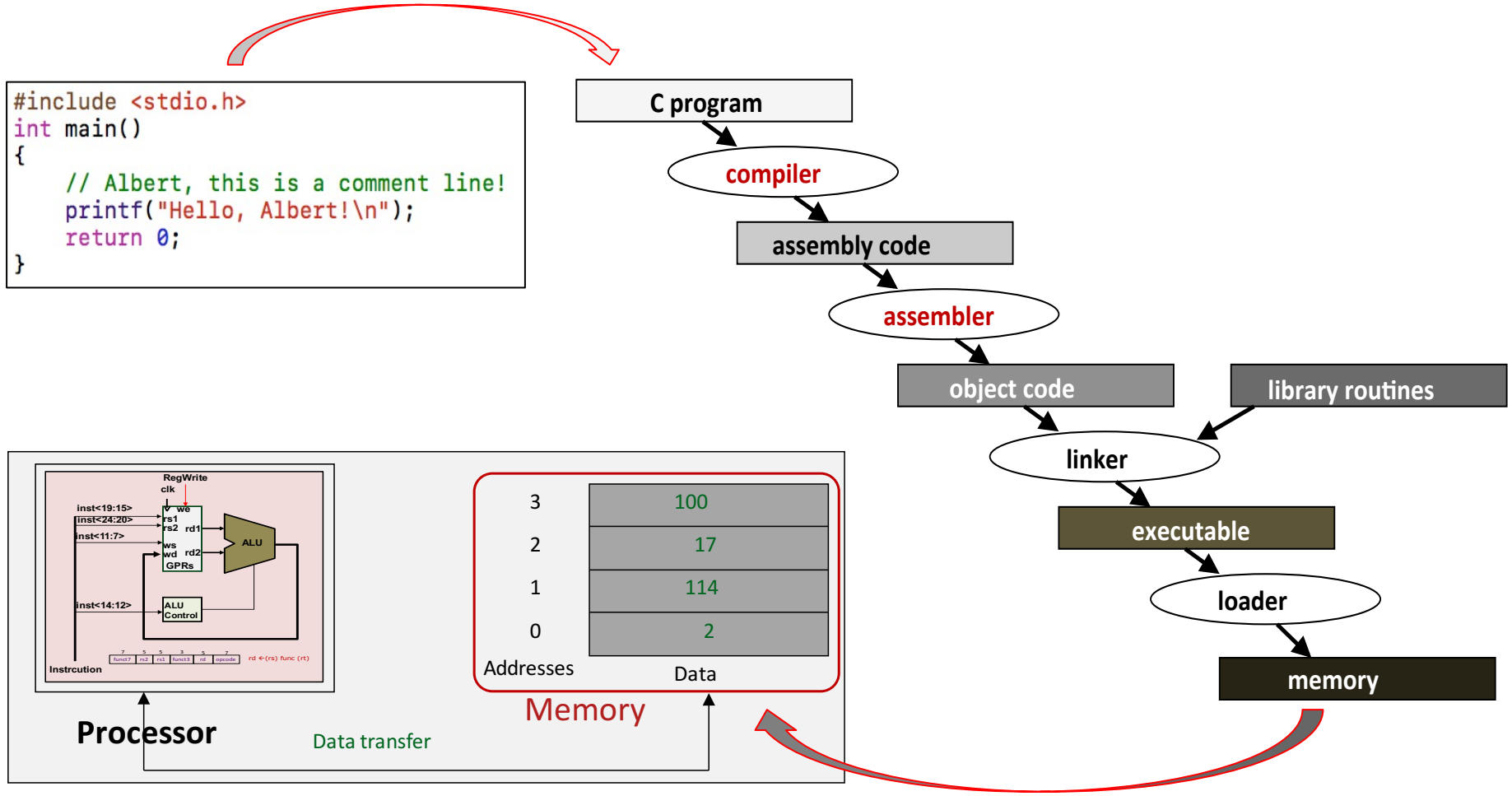


Data Addressing Modes

- Other memory address modes (non RISC-V)
  - Direct or absolute
    - add x1,(1024)
    - x1 ← x1+Mem[1024]
  - Memory indirect
    - add x1,@(x3)
    - x1 ← x1+Mem[Mem[x3]]



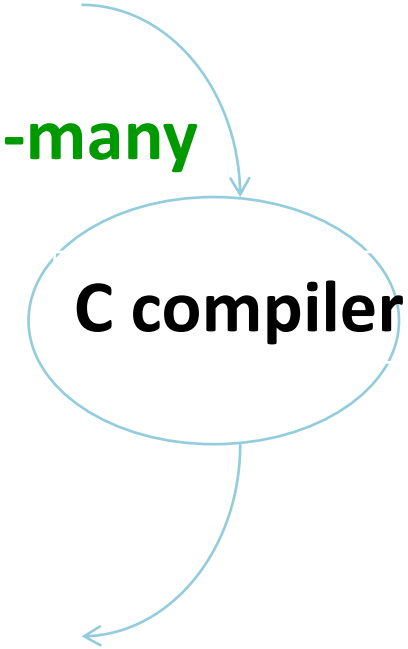
The Big Picture



Application Compiling Process

- High-level language program (in C)

```
void swap (int array[], int i) {
    int temp;
    temp       = array[i];
    array[i]   = array[i+1];
    array[i+1] = temp;
}
```



- Assembly language program (for RISC-V)

```
swap:
  addi sp,sp,-48
  ...
  mv a5,a1
  ...
  ld s0,40(sp)
  addi sp,sp,48
  jr ra
```

Application Compiling Process

- Assembly language program (for RISC-V)

```
swap:
  addi sp,sp,-48
  ...
  mv a5,a1
  ...
  ld s0,40(sp)
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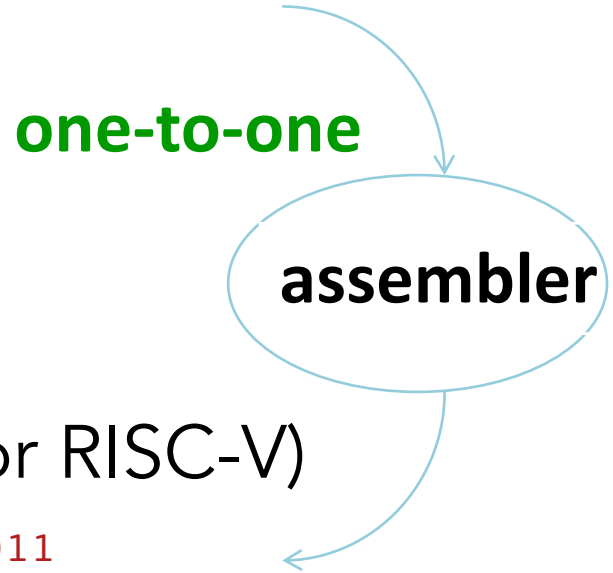


- Machine (object, binary) code (for RISC-V)

```
111111010000   00010   000 00010   0010011
000000110000   00010   000 01000   0010011
...
```

Application Compiling Process

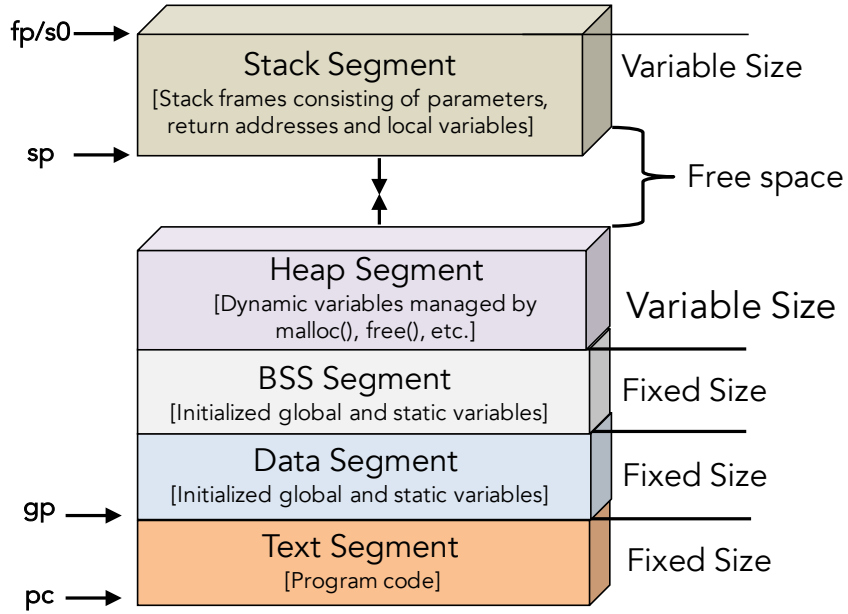
- Assembler (or compiler) translates program into machine instructions
- Provides information for building a complete program from the pieces
  - Header: described contents of object module
  - Text segment: translated instructions
  - Static data segment: data allocated for the life of the program
  - Relocation info: for contents that depend on absolute location of loaded program
  - Symbol table: global definitions and external refs
  - Debug info: for associating with source code

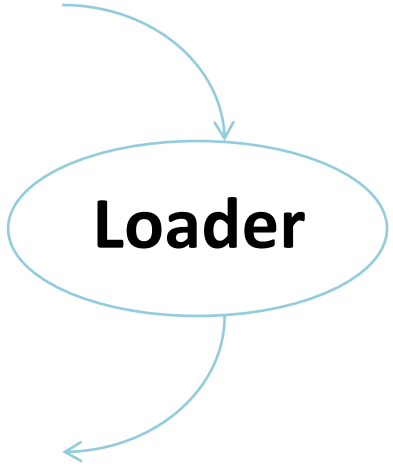
Application Compiling Process

- Machine (object, binary) code (for RISC-V)

```
111111010000   00010   000 00010   0010011
000000110000   00010   000 01000   0010011
```

- Memory organization





Application Compiling Process

- Load from image file on disk into memory
  1. Read header to determine segment sizes
  2. Create virtual address space
  3. Copy text and initialized data into memory
  4. Set up arguments on stack
  5. Initialize registers (including sp, fp, gp)
  6. Jump to startup routine
- Copies arguments to a0, … and calls main

The Big Idea in Today's Computers

- Stored Program Computer

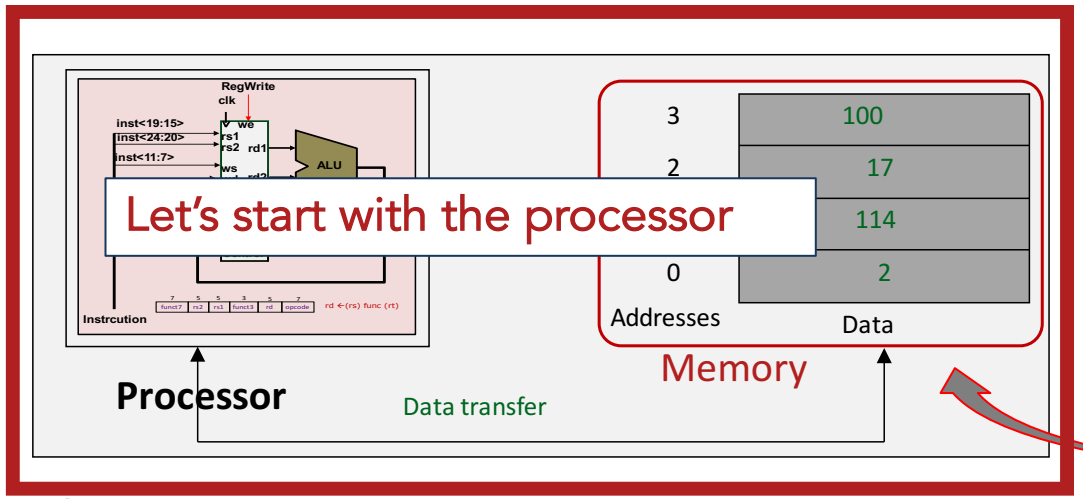
Program = A sequence of instructions

  - Instructions represented in binary, just like data
  - Instructions and data stored in memory
  - Programs can operate on programs
    - e.g., compilers, linkers, …
  - Binary compatibility allows compiled programs to work on different computers
    - Standardized ISAs

The Big Picture

```
#include <stdio.h>
int main()
{
    // Albert, this is a comment line!
    printf("Hello, Albert!\n");
    return 0;
}
```

C program → compiler → assembly code → assembler → object code + library routines → linker → executable → loader



Albert! It is time to build the computer from the ground up

Next Lecture Module

- RISC-V ISA