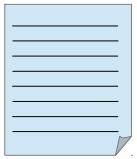
M2 – Instruction Set Architecture

Module Outline

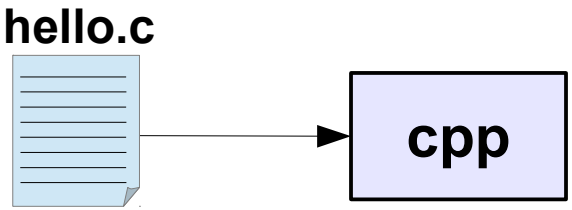
- Addressing modes. Instruction classes.
- MIPS-I ISA.
- Translating and starting a program.
- High level languages, Assembly languages and object code.
- Subroutine and subroutine call. Use of stack for handling subroutine call and return.

Steps in gcc

hello.c



Steps in gcc



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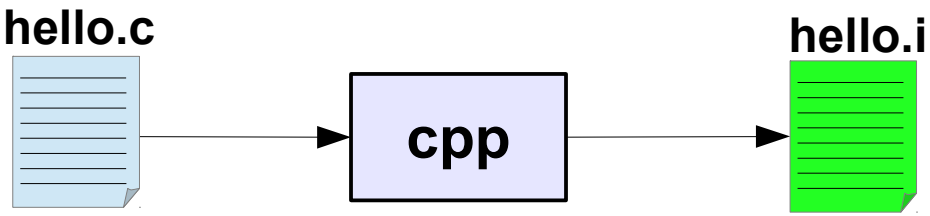

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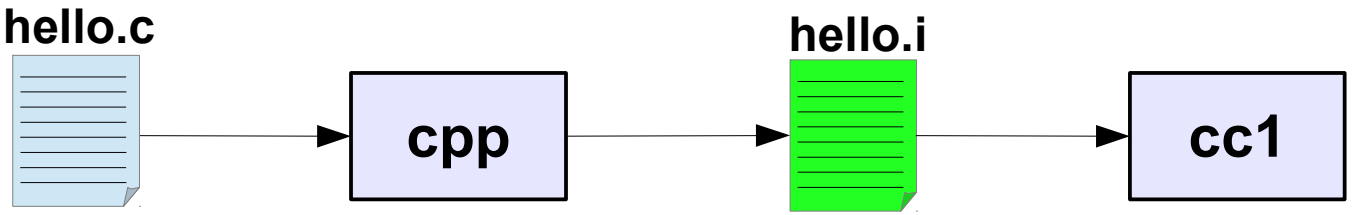

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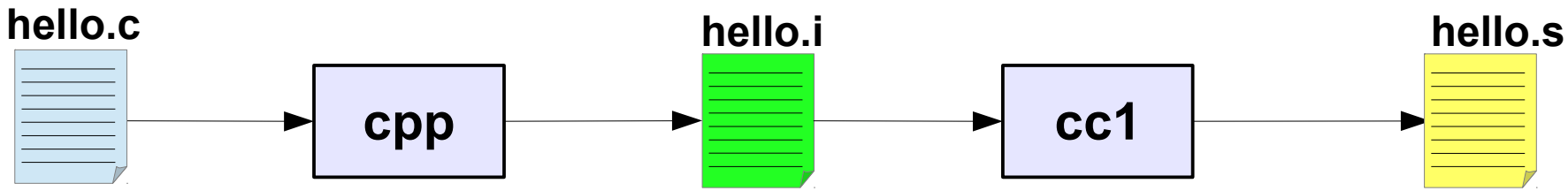
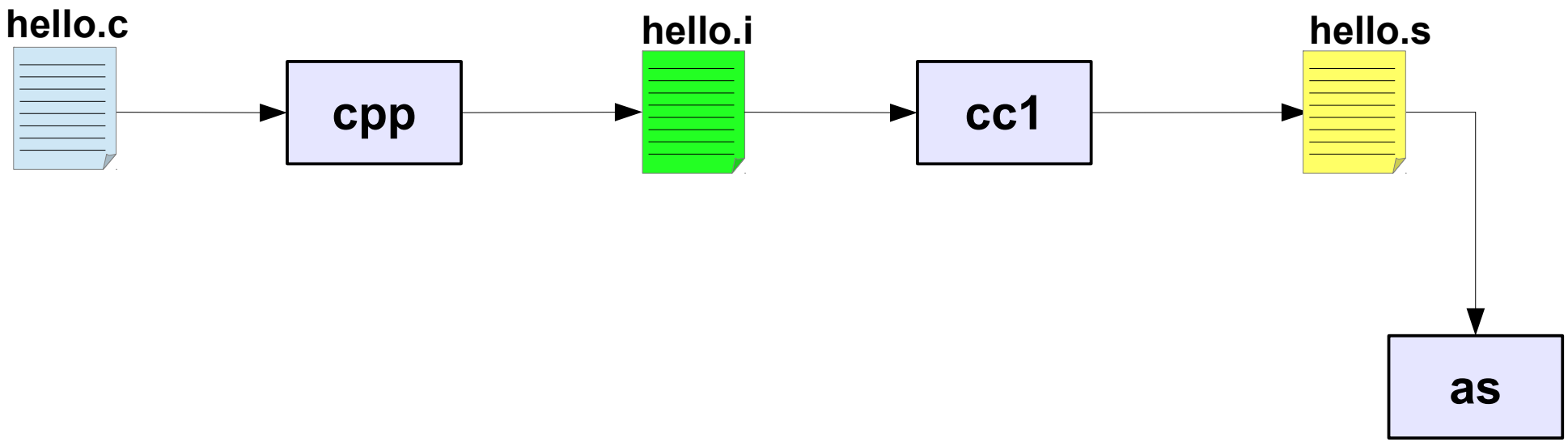


Steps in gcc



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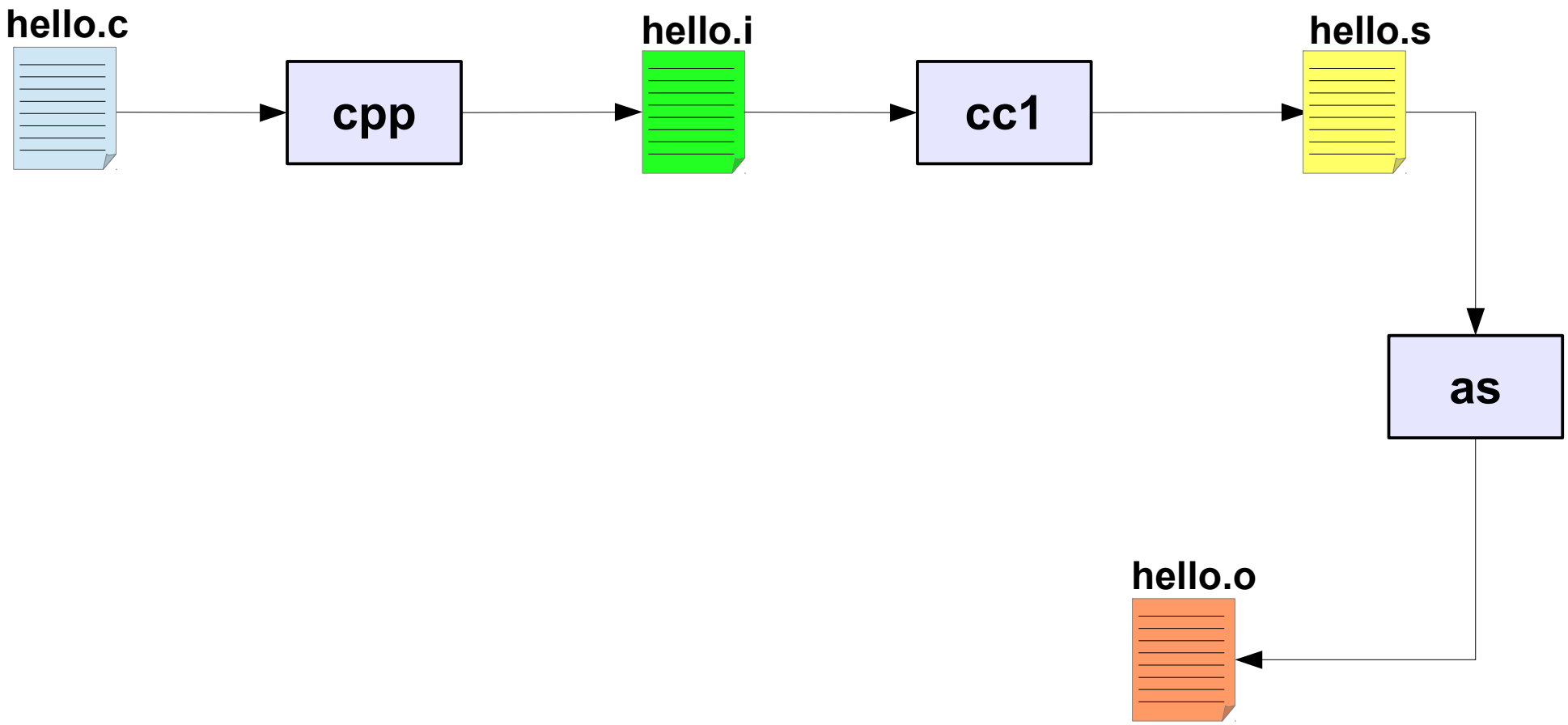

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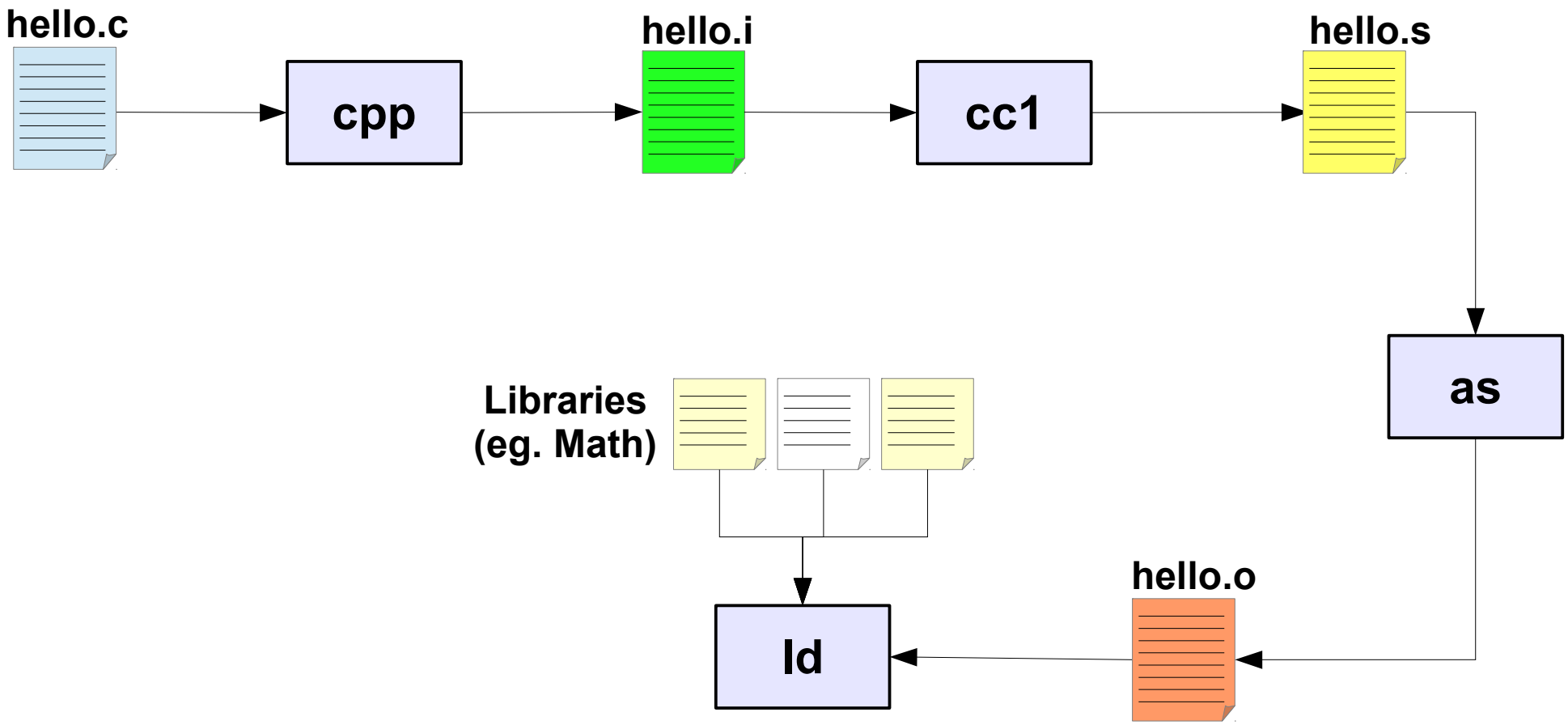

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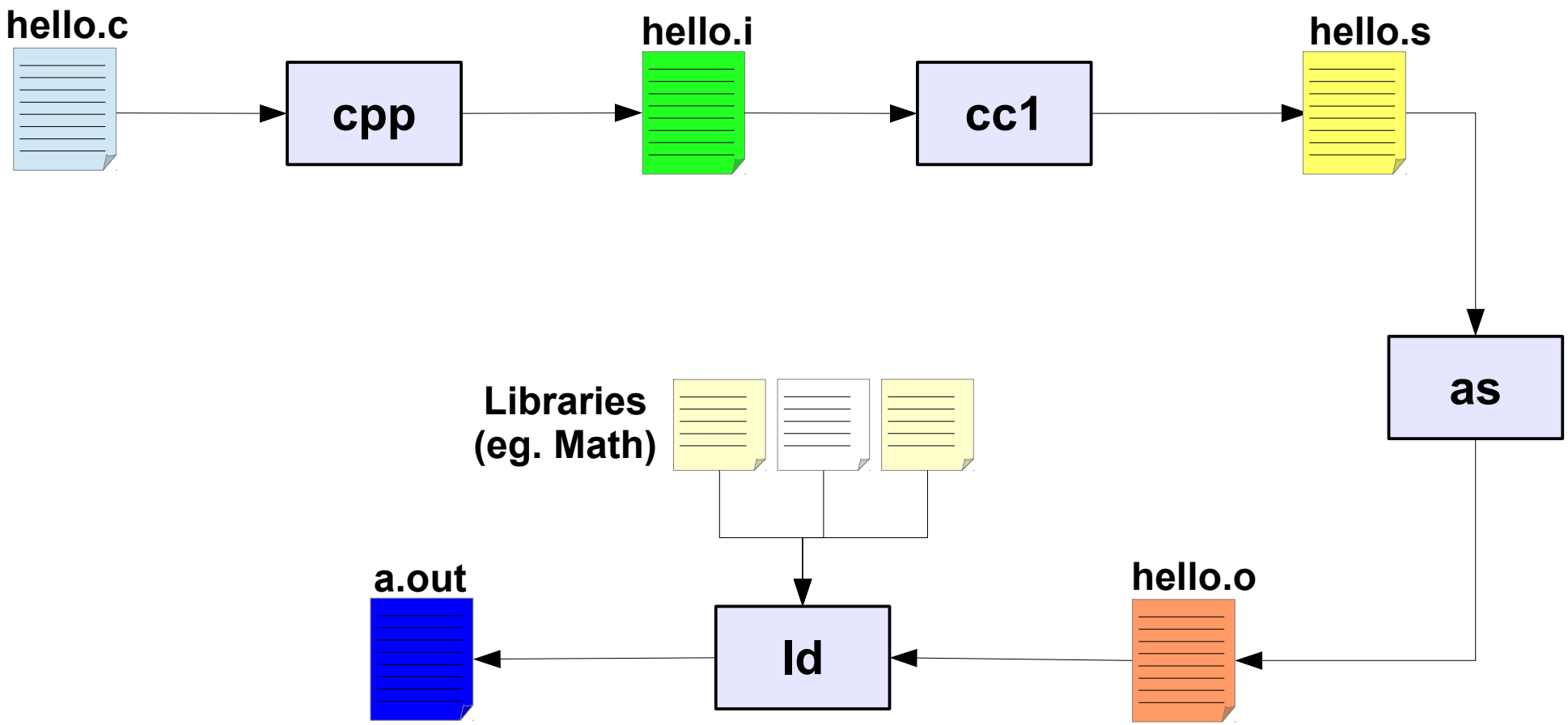
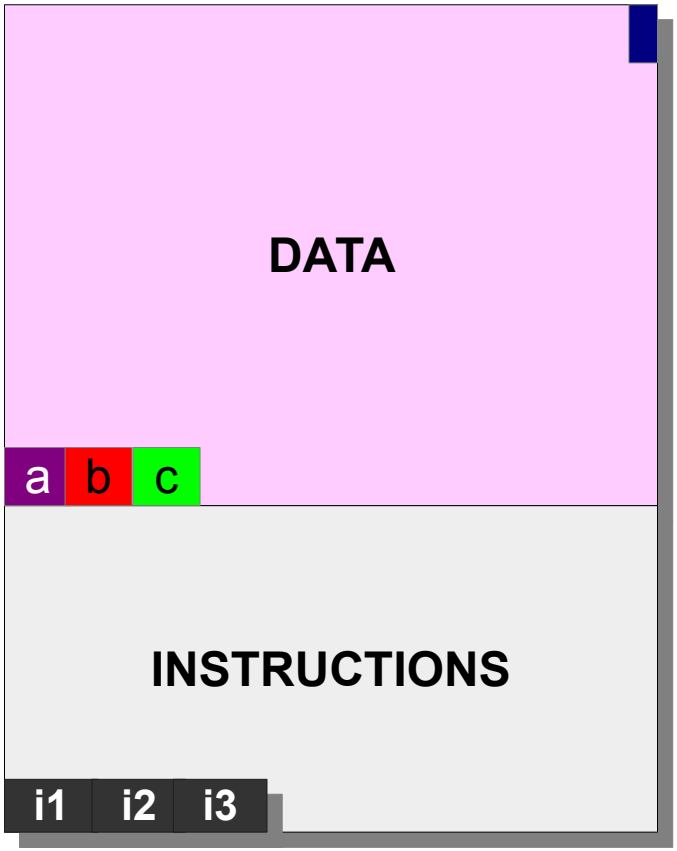

hello.c
cpp
hello.i
cc1
hello.s
as
Libraries
(eg. Math)
a.out
ld
hello.o

Steps in gcc

Step	Output	FileType	Remarks
C Preprocessor	hello.i	C source text	#include, #define, ...
C Compiler	hello.s	Assembler source text	Individual modules. Labels. Undefined global references.
Assembler	hello.o	Object code	
Linkage Editor	a.out	Executable	Global references resolved

Memory Layout of a Program in Execution



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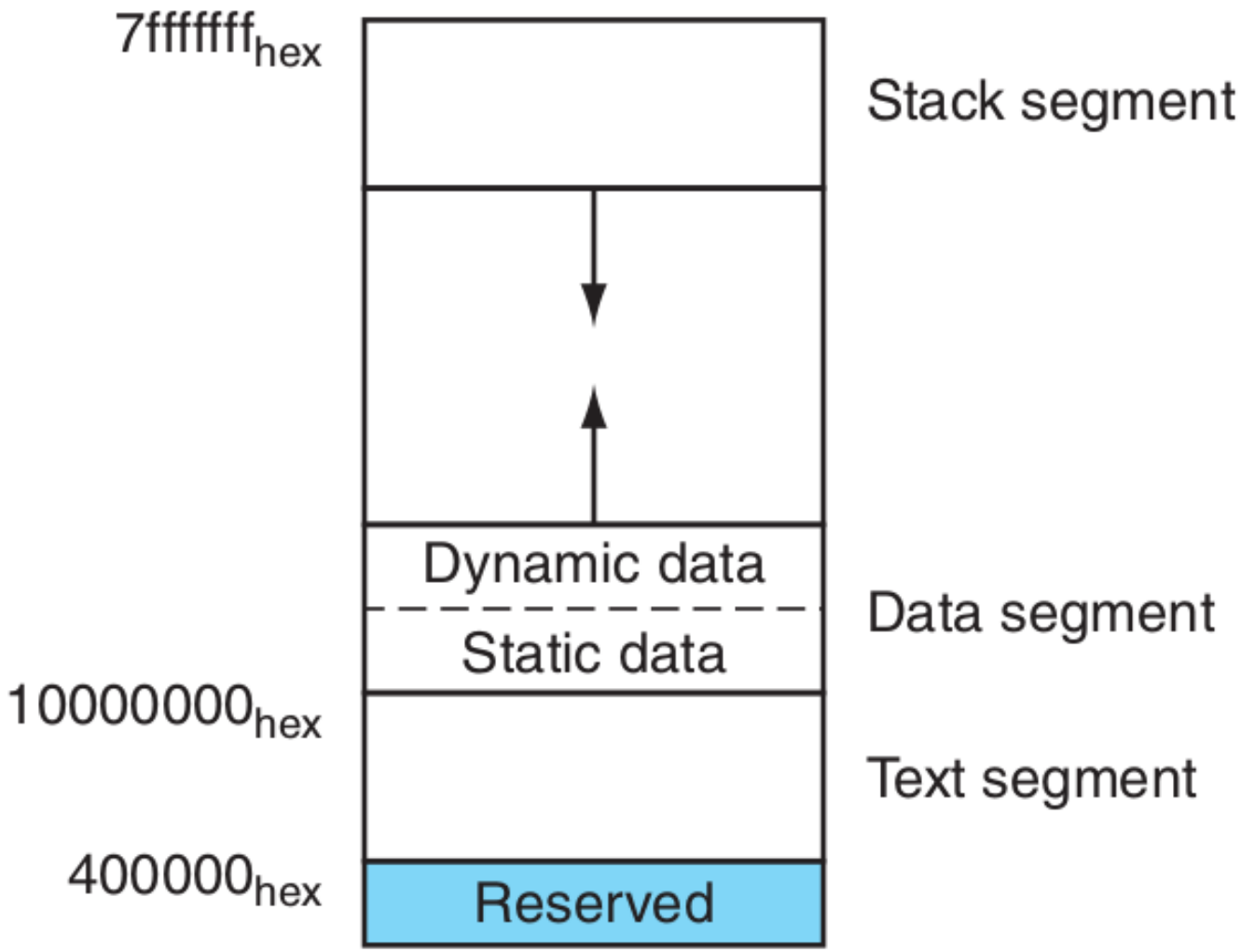

Program to Memory Layout

```
        .text
        .align  2
        .globl  main
main:
        subu    $sp, $sp, 32
        sw      $ra, 20($sp)
        sd      $a0, 32($sp)
        sw      $0,  24($sp)
        sw      $0,  28($sp)
loop:
        lw      $t6, 28($sp)
        mul     $t7, $t6, $t6
        lw      $t8, 24($sp)
        addu    $t9, $t8, $t7
        sw      $t9, 24($sp)
        addu    $t0, $t6, 1
        sw      $t0, 28($sp)
        ble     $t0, 100, loop
        la      $a0, str
        lw      $a1, 24($sp)
        jal     printf
        move    $v0, $0
        lw      $ra, 20($sp)
        addu    $sp, $sp, 32
        jr      $ra


        .data
        .align  0
str:
        .asciiz "The sum from 0 .. 100 is %d\n"
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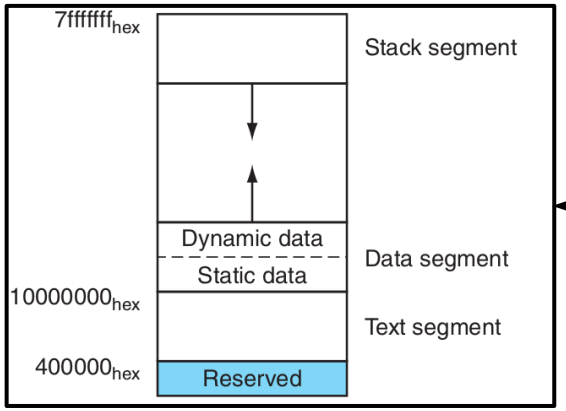
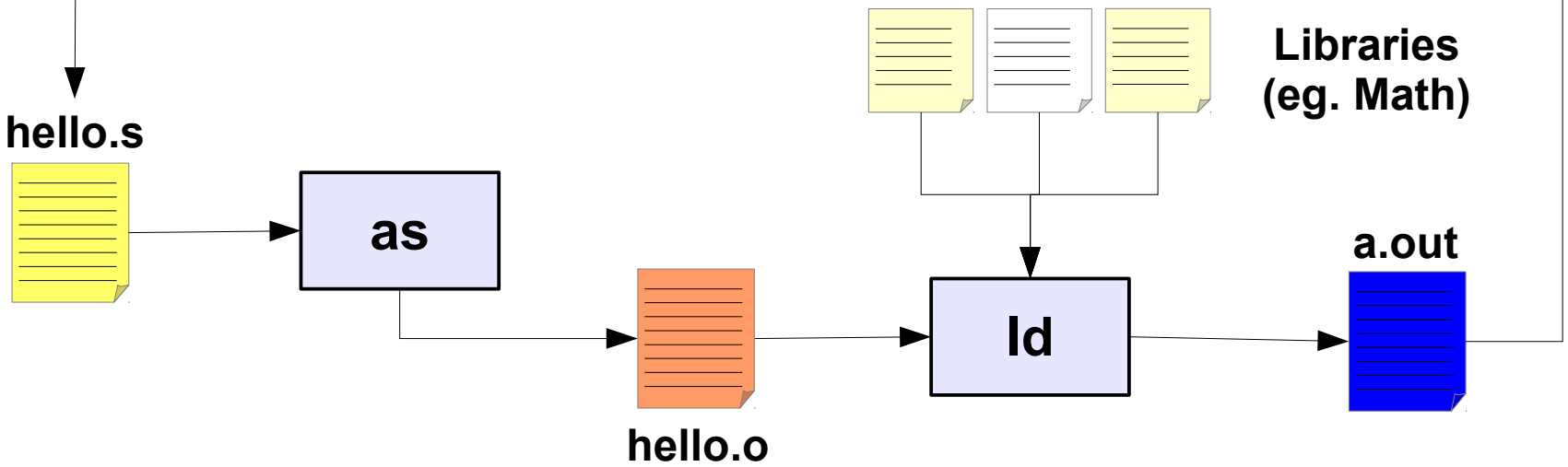
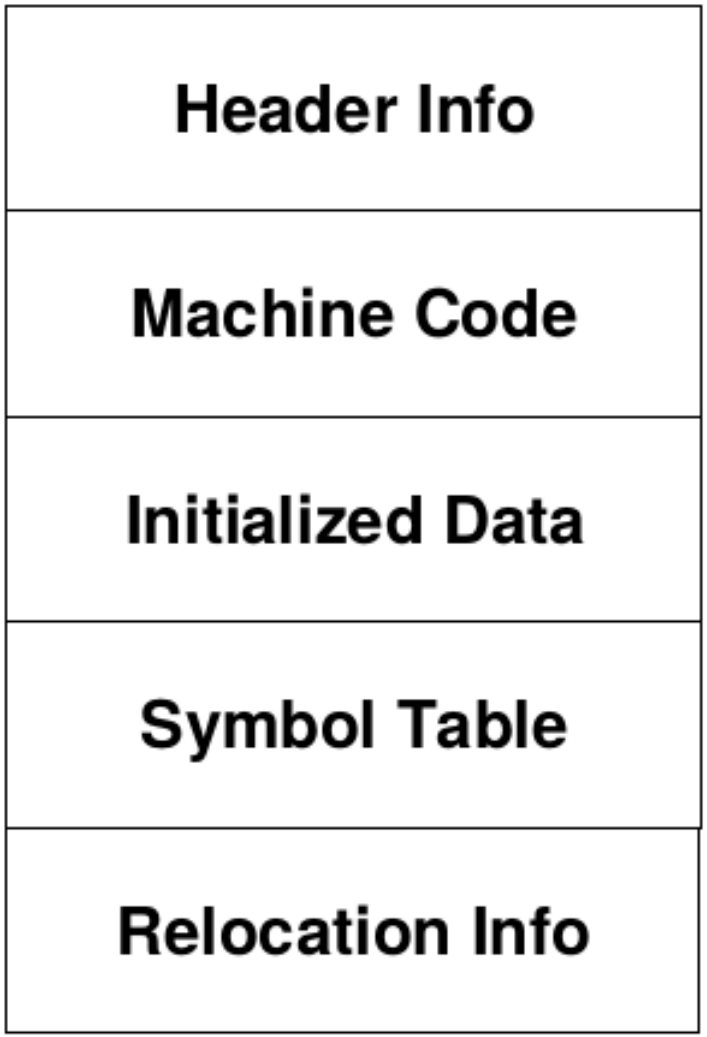




Object File Format (hello.o)



What does the Assembler do?

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Encodes easily!

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Assembler Directives

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Text segment begins here.
Align at word boundary.
main is a global “label”. Can be referred from other modules.

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        .data
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```

Text segment begins here.
Align at word boundary.
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Assembler Directives

Data segment begins here.
Align at byte boundary.

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```
        .text
        .align  2
        .globl  main
main:
        subu    $sp, $sp, 32
        sw      $ra, 20($sp)
        sd      $a0, 32($sp)
        sw      $0,  24($sp)
        sw      $0,  28($sp)
loop:
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Labels

What does the Assembler do?

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        .data
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str:
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```

Labels

Assembler Actions

```
ble     $t0, 100, loop
la      $a0, str
```

- How to encode?
- What information is required?

Assembler Actions

```
ble     $t0, 100, loop
la      $a0, str
```

- How to encode?
- Information required:
  - Where to branch? Where is “loop”?
  - Where is “str”?

Assembler Actions

- Labels – `main, loop, str` are names for memory locations.

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  - main: first instruction in the text segment
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loop	20
str	800
printf	??

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  - printf: undefined
- Symbol Table

main	0
loop	20
str	800
printf	??

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Library Function Call

Unresolved references

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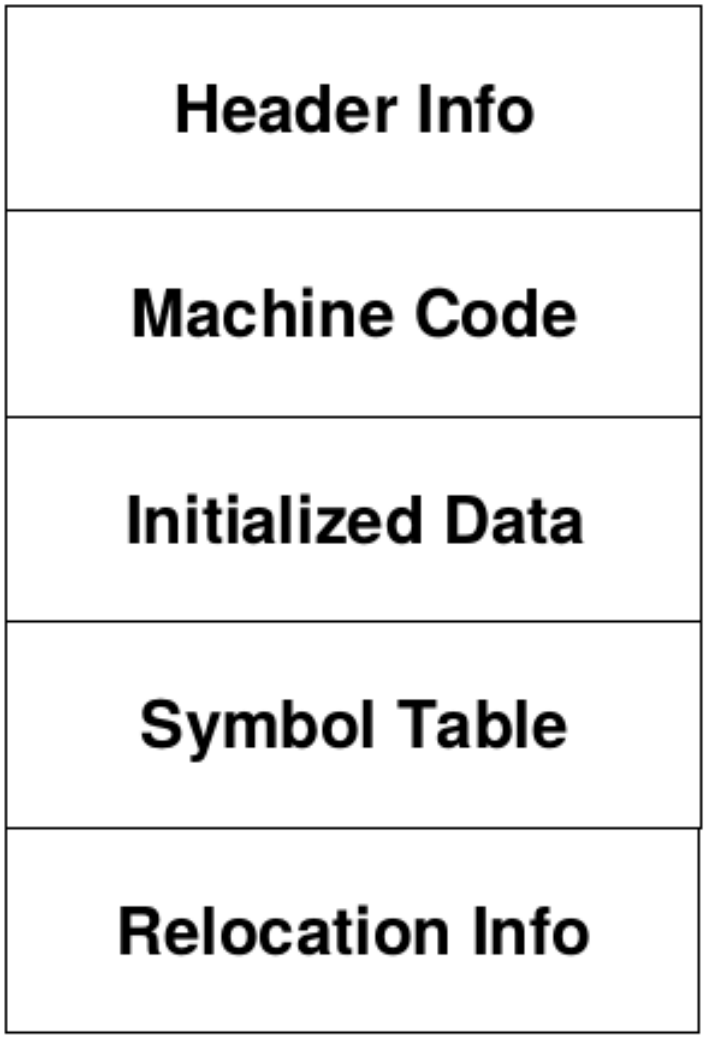
64	call	printf	??

Object File Format (hello.o)



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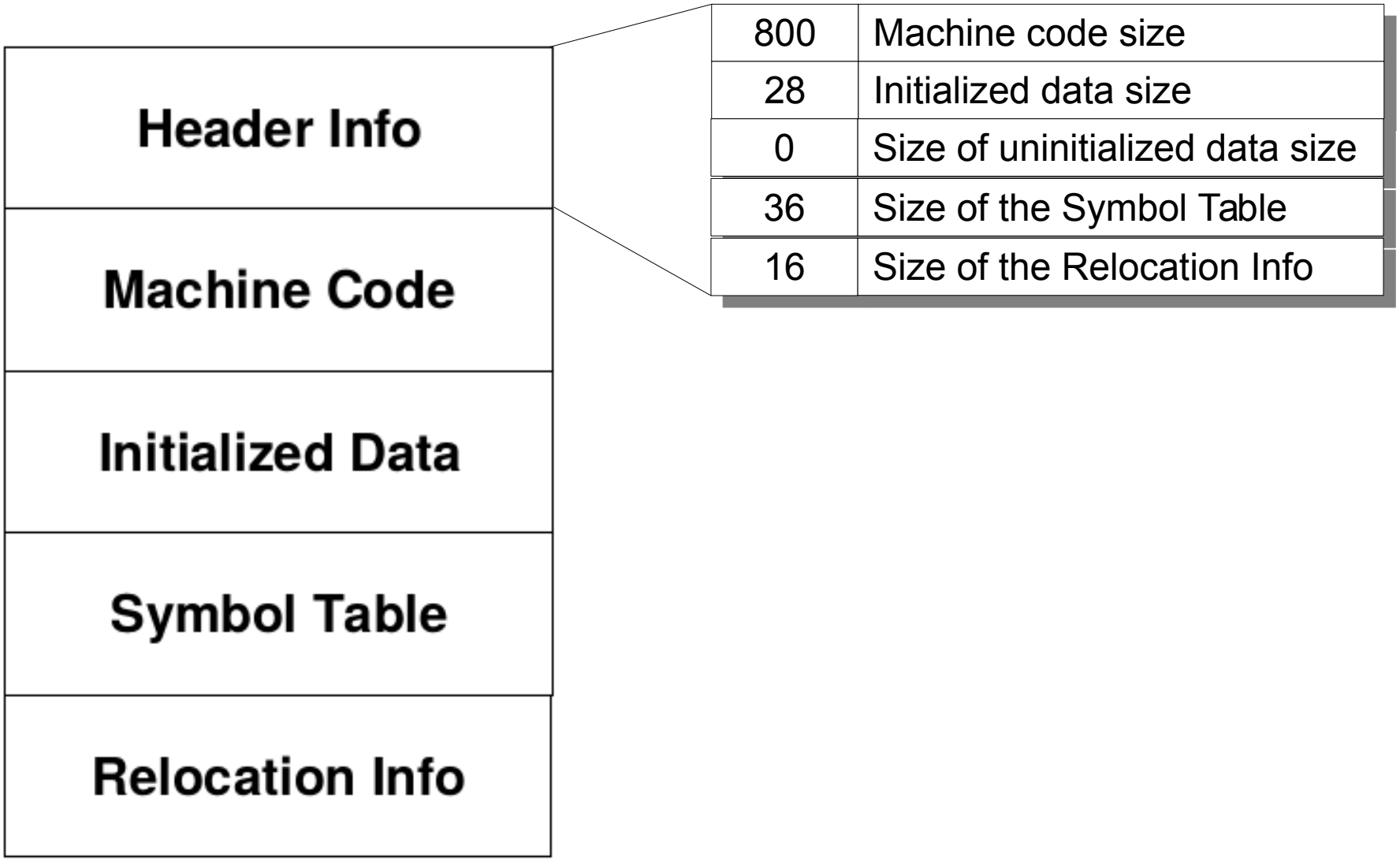

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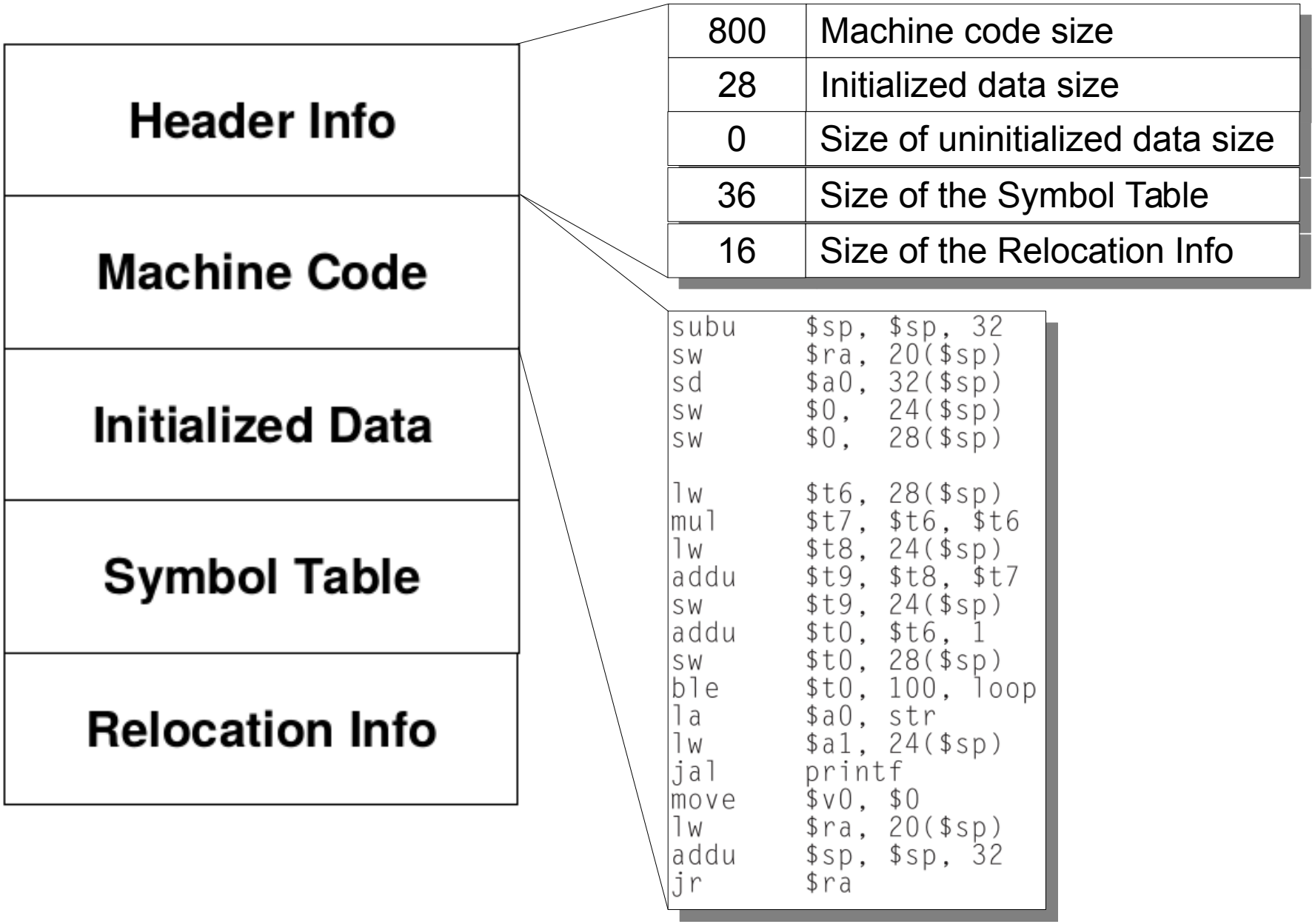

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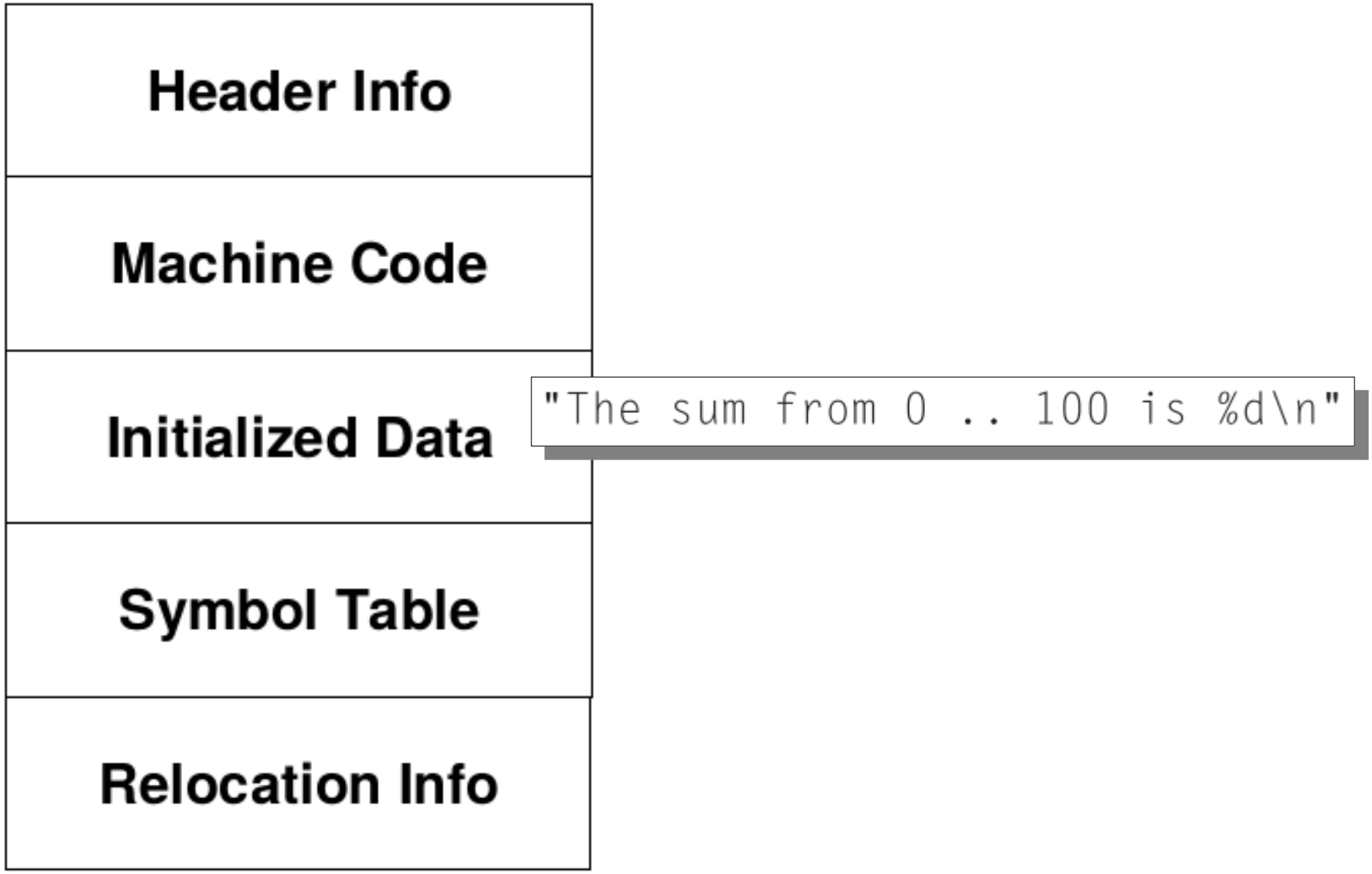

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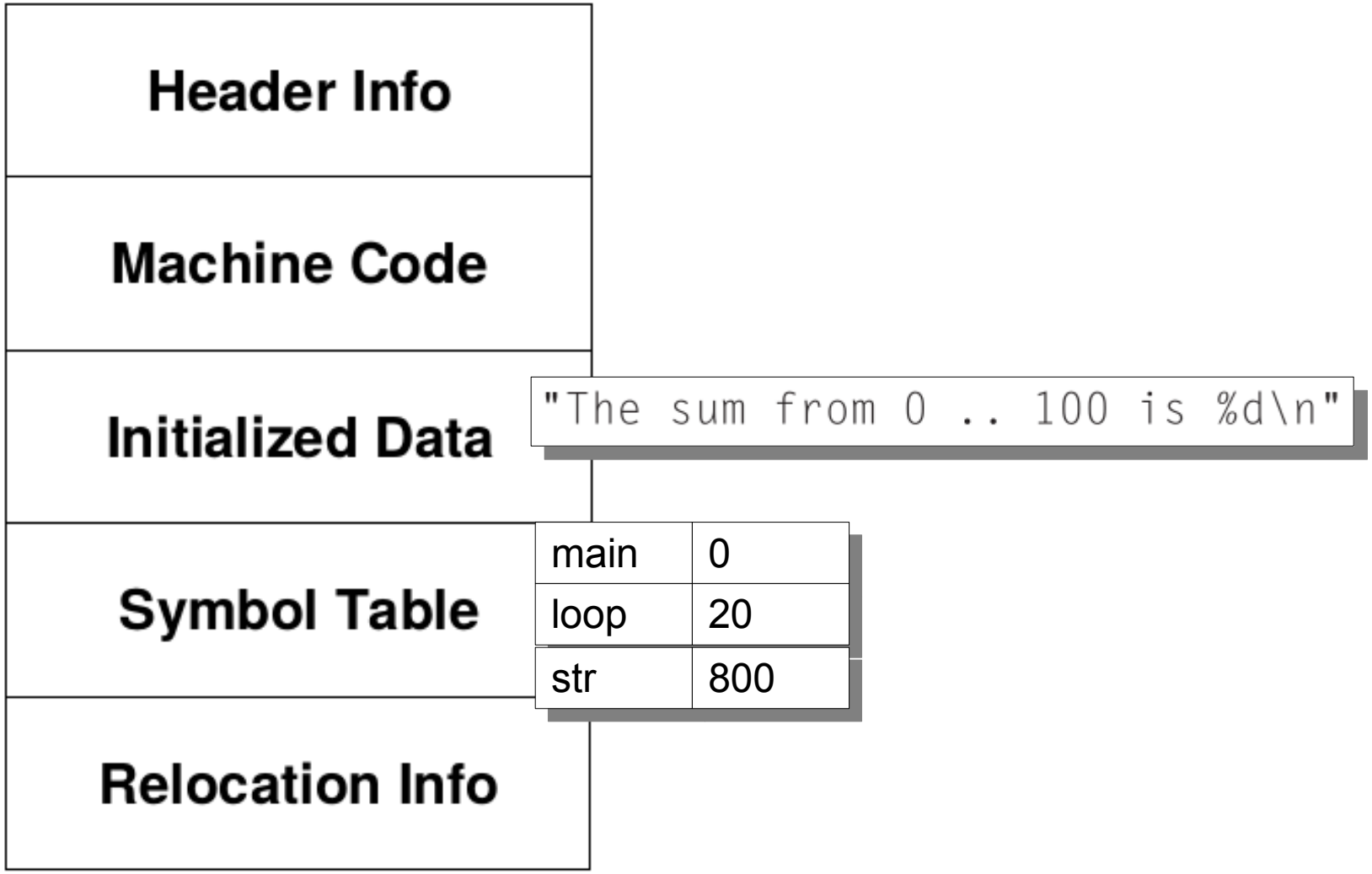

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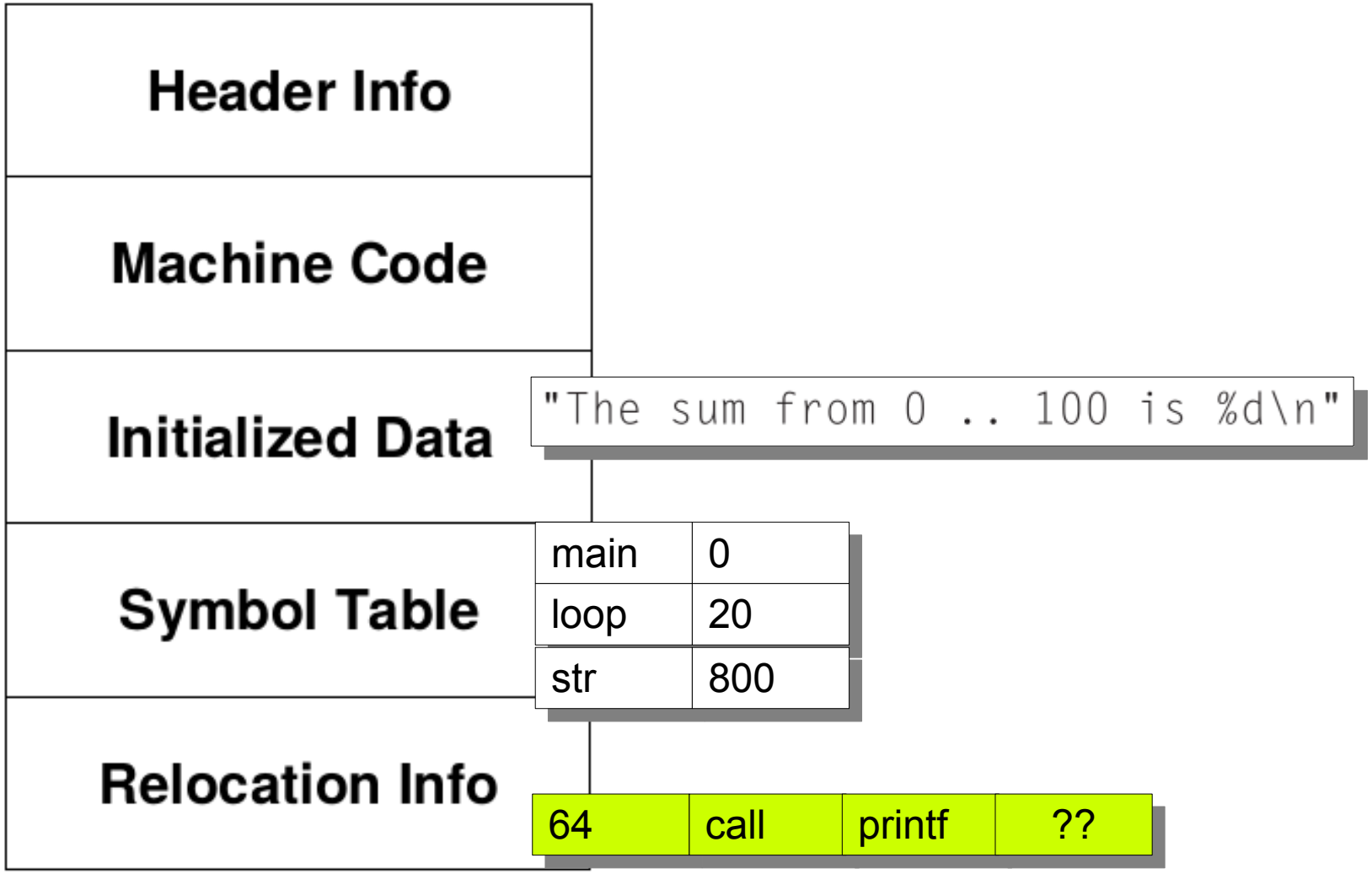

Assembler

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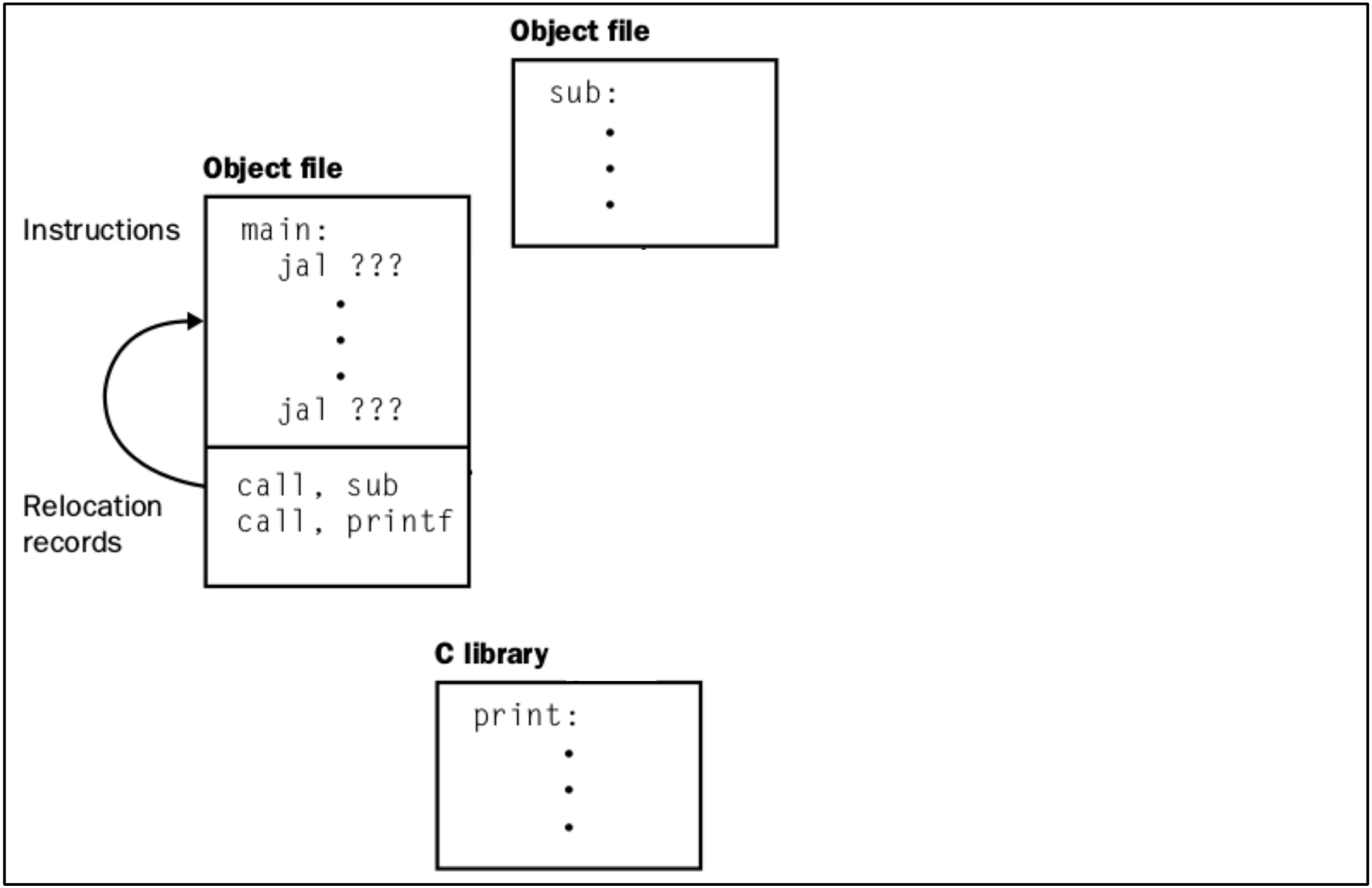
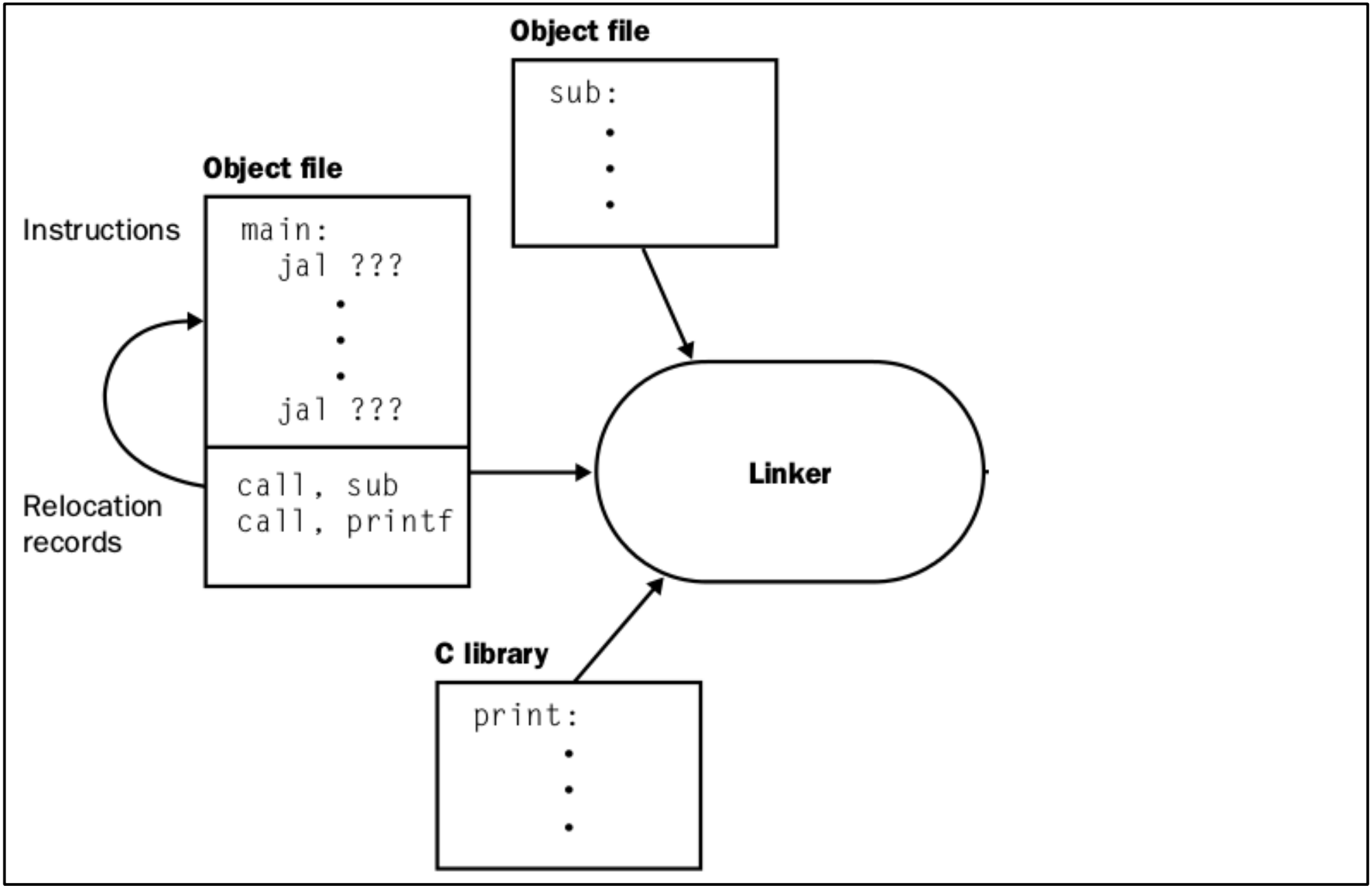
- Pass 2: Translate each assembly statement by combining the numeric equivalents of opcodes, register specifiers, and labels into a legal instruction.

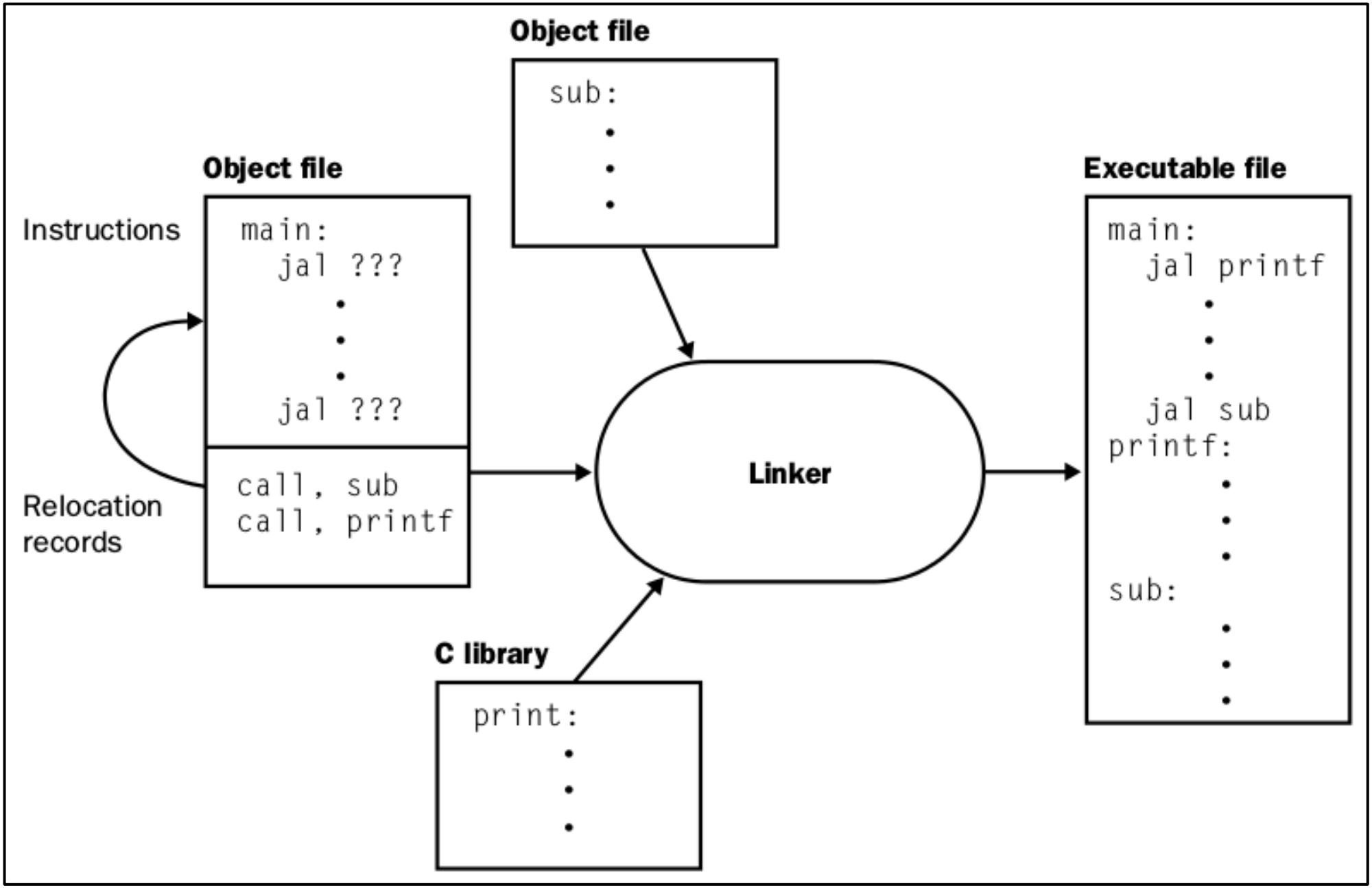
Linking Multiple Modules



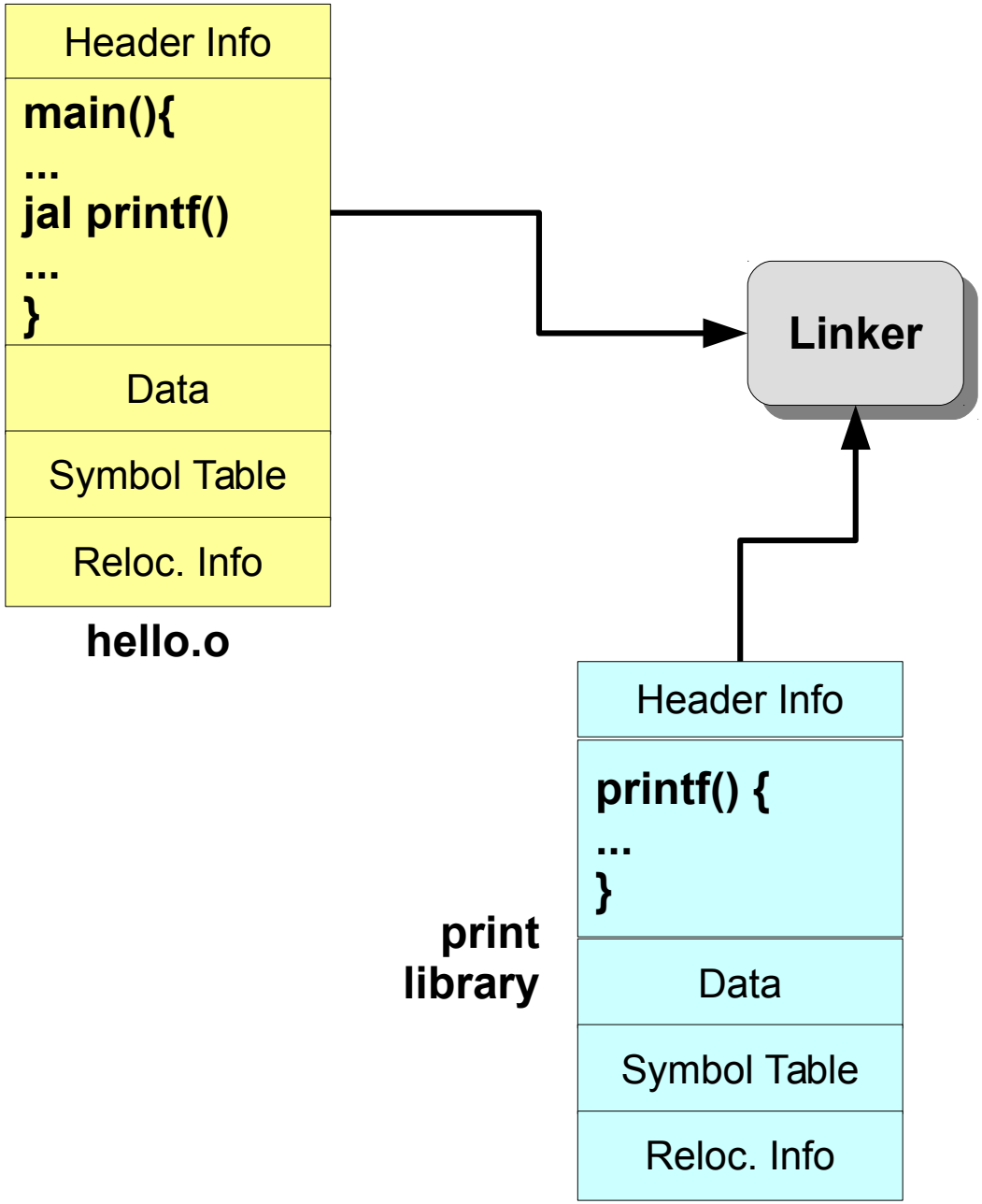
Linking Multiple Modules



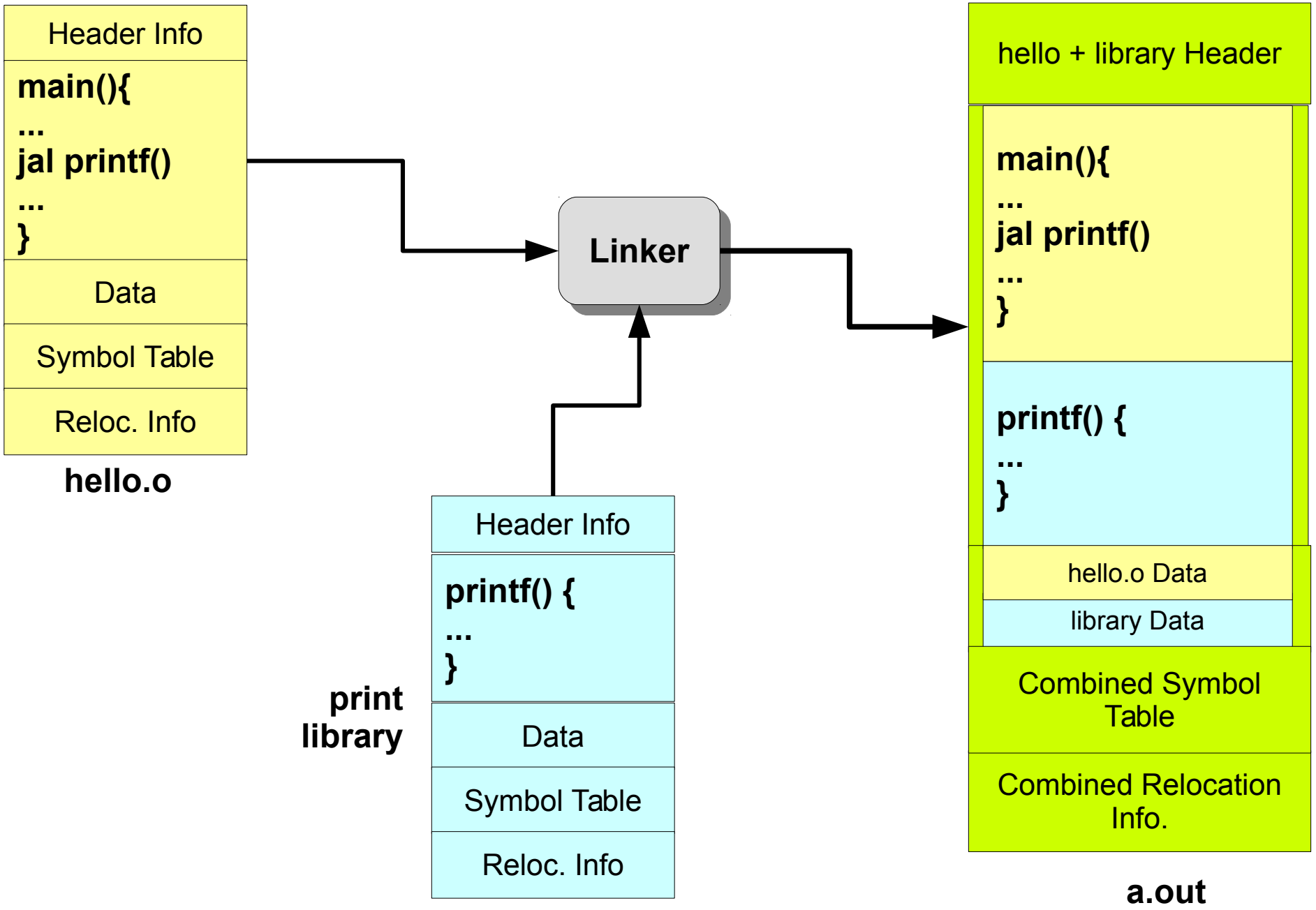
Linking Multiple Modules



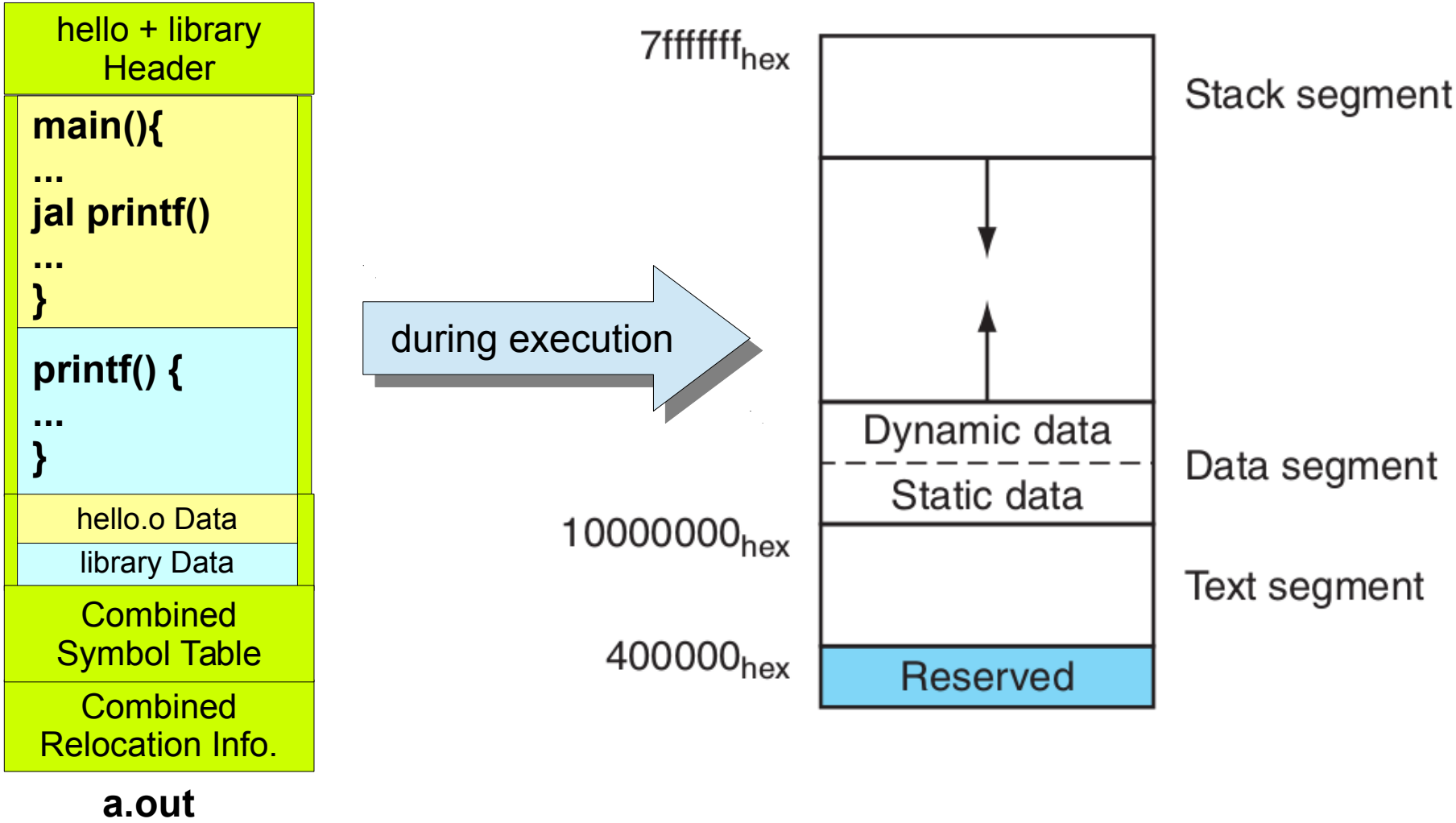
Linking Multiple Modules



Linking Multiple Modules



Memory Layout of a.out



Linking Example

- Link modules procedureA and procedureB

```
procedureA:
 ...
  la $gp, X
  lw $a0, 0($gp)
  jal B
 ...

.data
 .word X
```

```
procedureB:
 ...
  la $gp, Y
  sw $a0, 0($gp)
  jal A
 ...

.data
 .word Y
```

Linking Example – Procedure A

Object file header			
Text segment	Address	Instruction	
	0	lw $a0, 0($gp)	
	4	jal 0	
	...	...	
Data segment			
Relocation information			
Symbol table			

Linking Example – Procedure A

Object file header			
Text segment	Address	Instruction	
	0	lw $a0, 0($gp)	
	4	jal 0	
	...	...	
Data segment	0	(X)	
	...	...	
Relocation information			
Symbol table			

Linking Example – Procedure A

Object file header			
Text segment	Address	Instruction	
	0	lw $a0, 0($gp)	
	4	jal 0	
	...	...	
Data segment	0	(X)	
	...	...	
Relocation information			
Symbol table	Label	Address	
	X	–	
	B	–	

Linking Example – Procedure A

Object file header			
Text segment	Address	Instruction	
	0	lw $a0, 0($gp)	
	4	jal 0	
	...	...	
Data segment	0	(X)	
	...	...	
Relocation information	Address	Instruction type	Dependency
	0	lw	X
	4	jal	B
Symbol table	Label	Address	
	X	–	
	B	–	

Linking Example – Procedure A

Object file header			
	Name	Procedure A	
	Text size	100_{hex}	
	Data size	20_{hex}	
Text segment	Address	Instruction	
	0	`lw $a0, 0($gp)`	
	4	`jal 0`	
	...	...	
Data segment	0	(X)	
	...	...	
Relocation information	Address	Instruction type	Dependency
	0	`lw`	X
	4	`jal`	B
Symbol table	Label	Address	
	X	–	
	B	–	

Linking Example – Procedure B

Object file header			
Text segment	Address	Instruction	
	0	sw $a1, 0($gp)	
	4	jal 0	
	...	...	
Data segment			
Relocation information	Address	Instruction type	Dependency
	0	sw	Y
	4	jal	A
Symbol table			

Linking Example – Procedure B

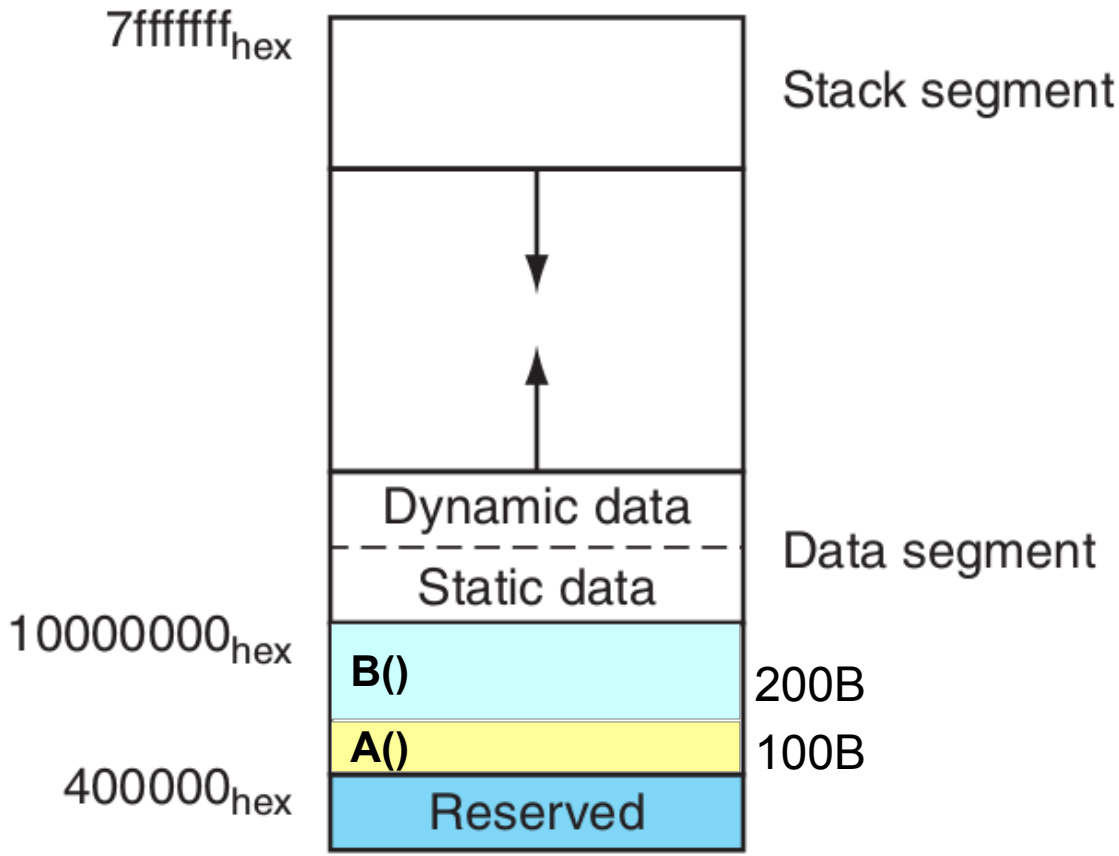
Object file header			
Text segment	Address	Instruction	
	0	sw $a1, 0($gp)	
	4	jal 0	
	...	...	
Data segment	0	(Y)	
	...	...	
Relocation information	Address	Instruction type	Dependency
	0	sw	Y
	4	jal	A
Symbol table	Label	Address	
	Y	–	
	A	–	

Linking Example – Procedure B

Object file header			
	Name	Procedure B	
	Text size	200_{hex}	
	Data size	30_{hex}	
Text segment	Address	Instruction	
	0	sw $a1, 0($gp)	
	4	jal 0	
	...	...	
Data segment	0	(Y)	
	...	...	
Relocation information	Address	Instruction type	Dependency
	0	sw	Y
	4	jal	A
Symbol table	Label	Address	
	Y	–	
	A	–	

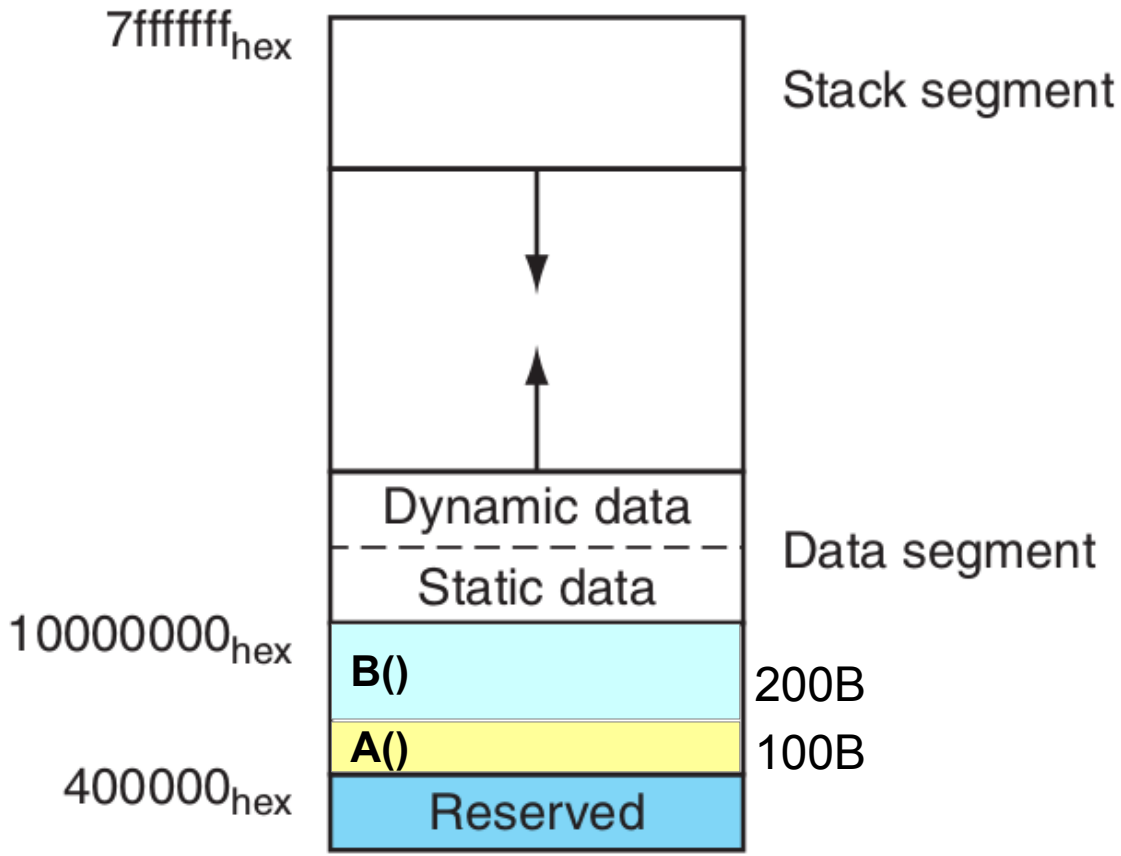
Linking Example

- Address of Procedure A?
- Address of Procedure B?



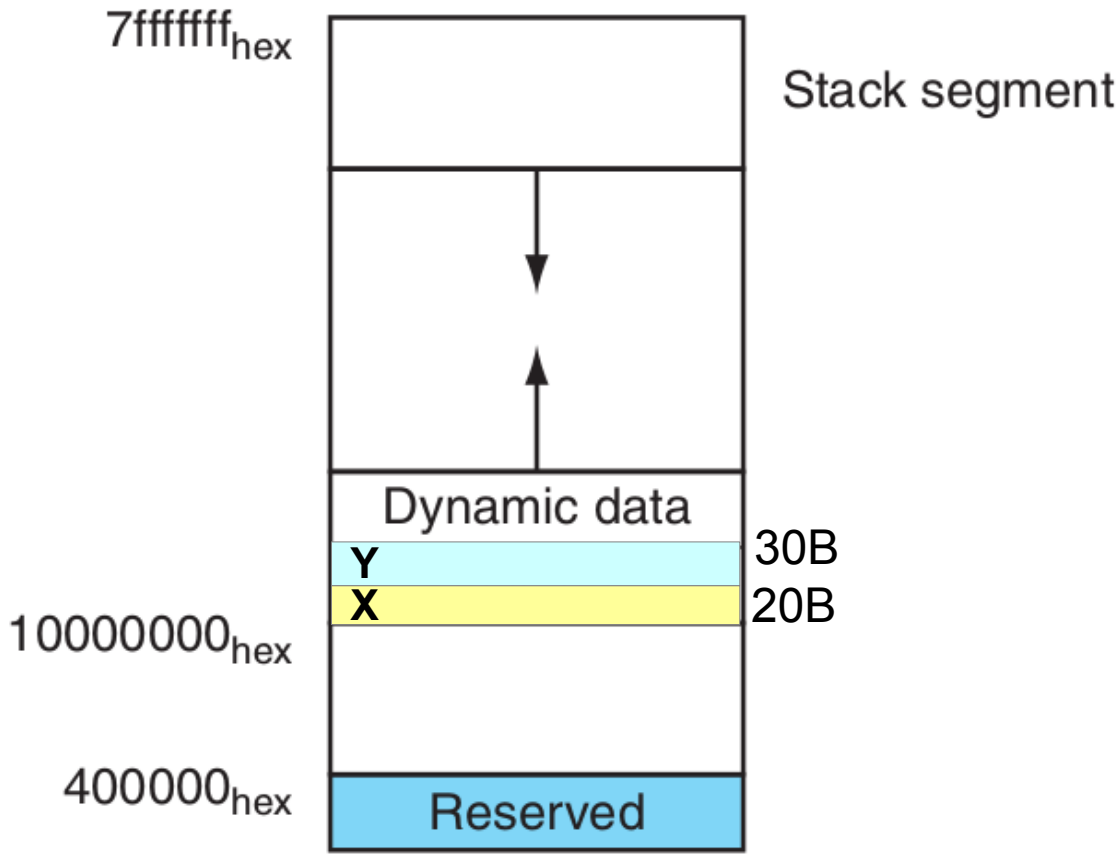
Linking Example

- Procedure A starts at 0x400000
- Procedure B starts at 0x400100



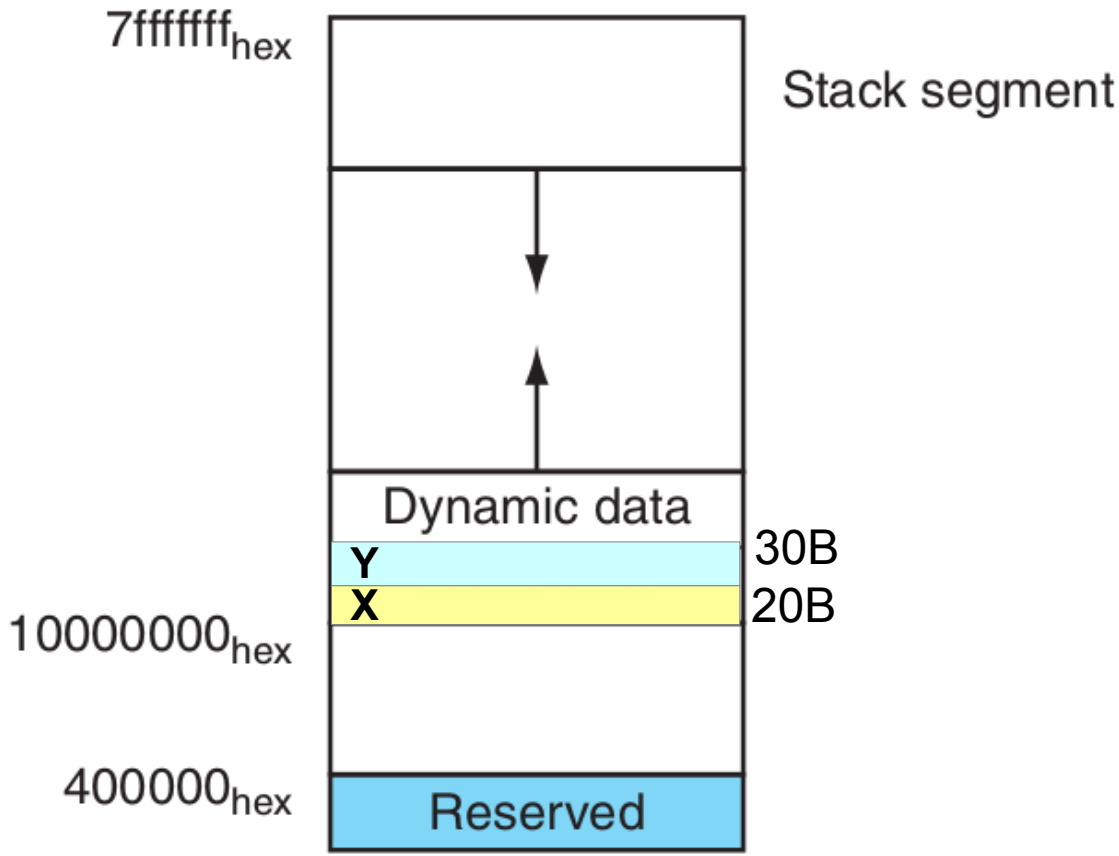
Linking Example

- Value of $gp?
- Addresses of X & Y?



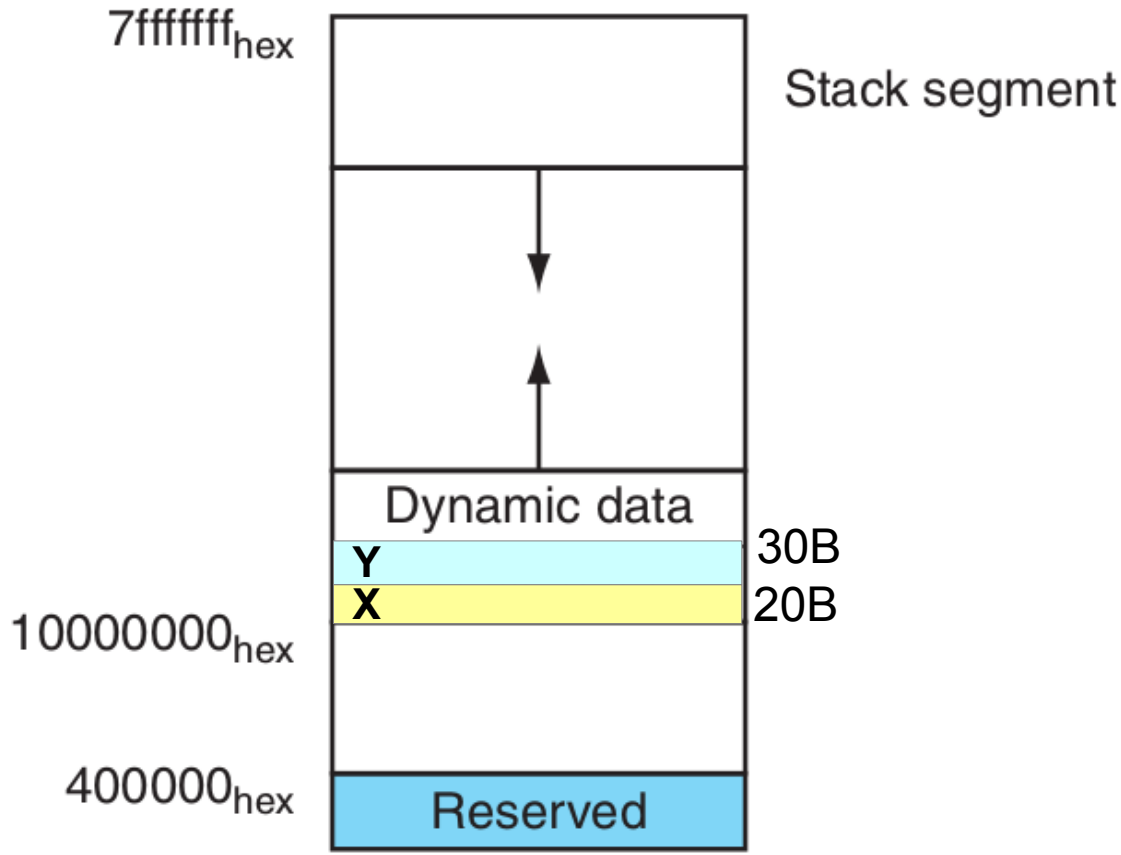
Linking Example

- Value of $gp?
- Addresses of X & Y?



Linking Example

- Value of $gp = 0x10008000
- X = 0x10000000
- Y = 0x10000020



Linking Example – a.out

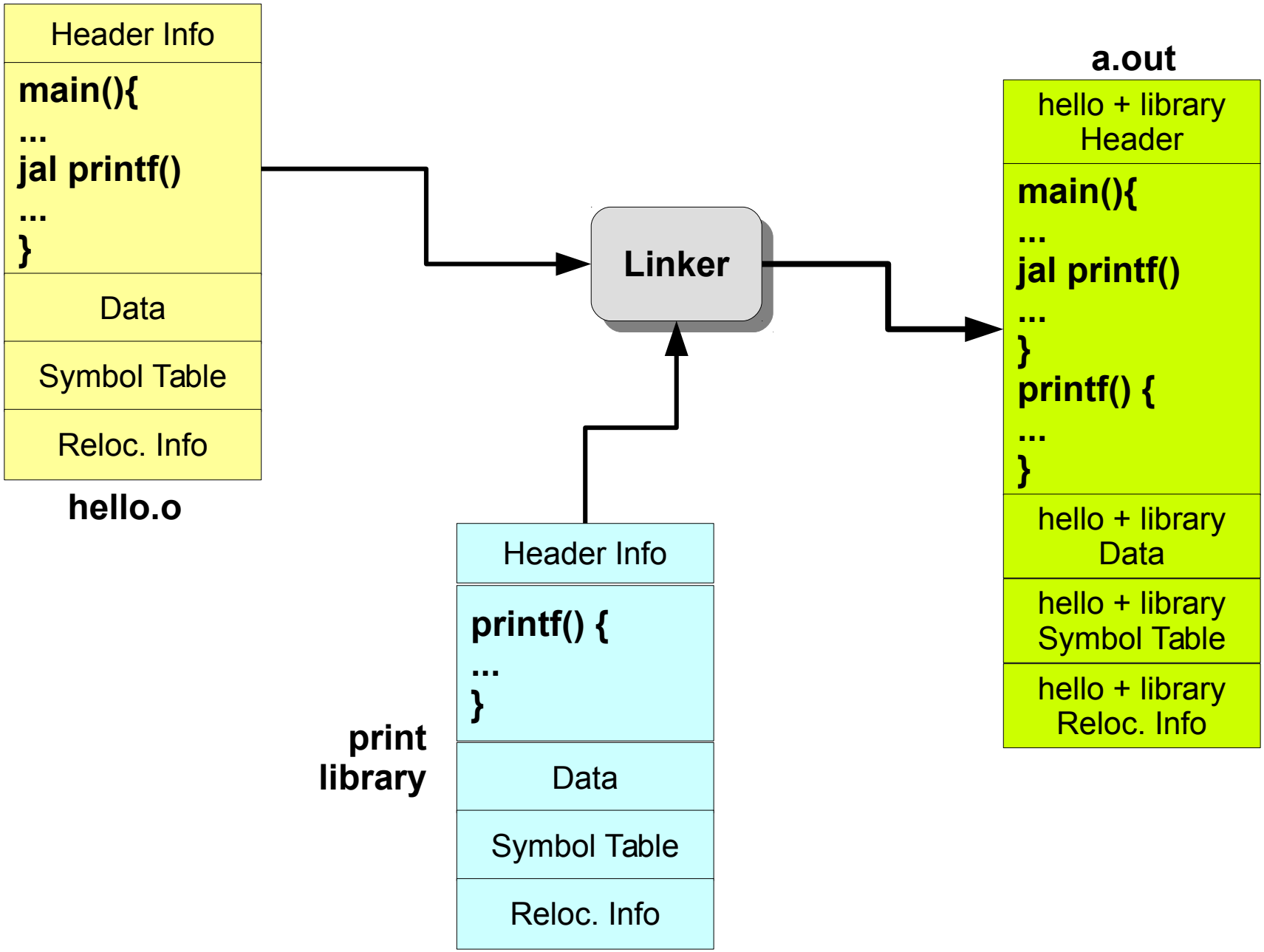
Executable file header		
	Text size	300_{hex}
	Data size	50_{hex}
Text segment	Address	Instruction
	$0040\ 0000_{hex}$	lw $a0, 8000_{hex}($gp)
	$0040\ 0004_{hex}$	jal $40\ 0100_{hex}$
	...	...
	$0040\ 0100_{hex}$	sw $a1, 8020_{hex}($gp)
	$0040\ 0104_{hex}$	jal $40\ 0000_{hex}$
	...	...
Data segment	Address	
	$1000\ 0000_{hex}$	(X)
	...	...
	$1000\ 0020_{hex}$	(Y)
	...	...

Module Outline

- Addressing modes. Instruction classes.
- MIPS-I ISA.
- Translating and starting a program.
- High level languages, Assembly languages and object code.
- Subroutine and subroutine call. Use of stack for handling subroutine call and return.

Backup

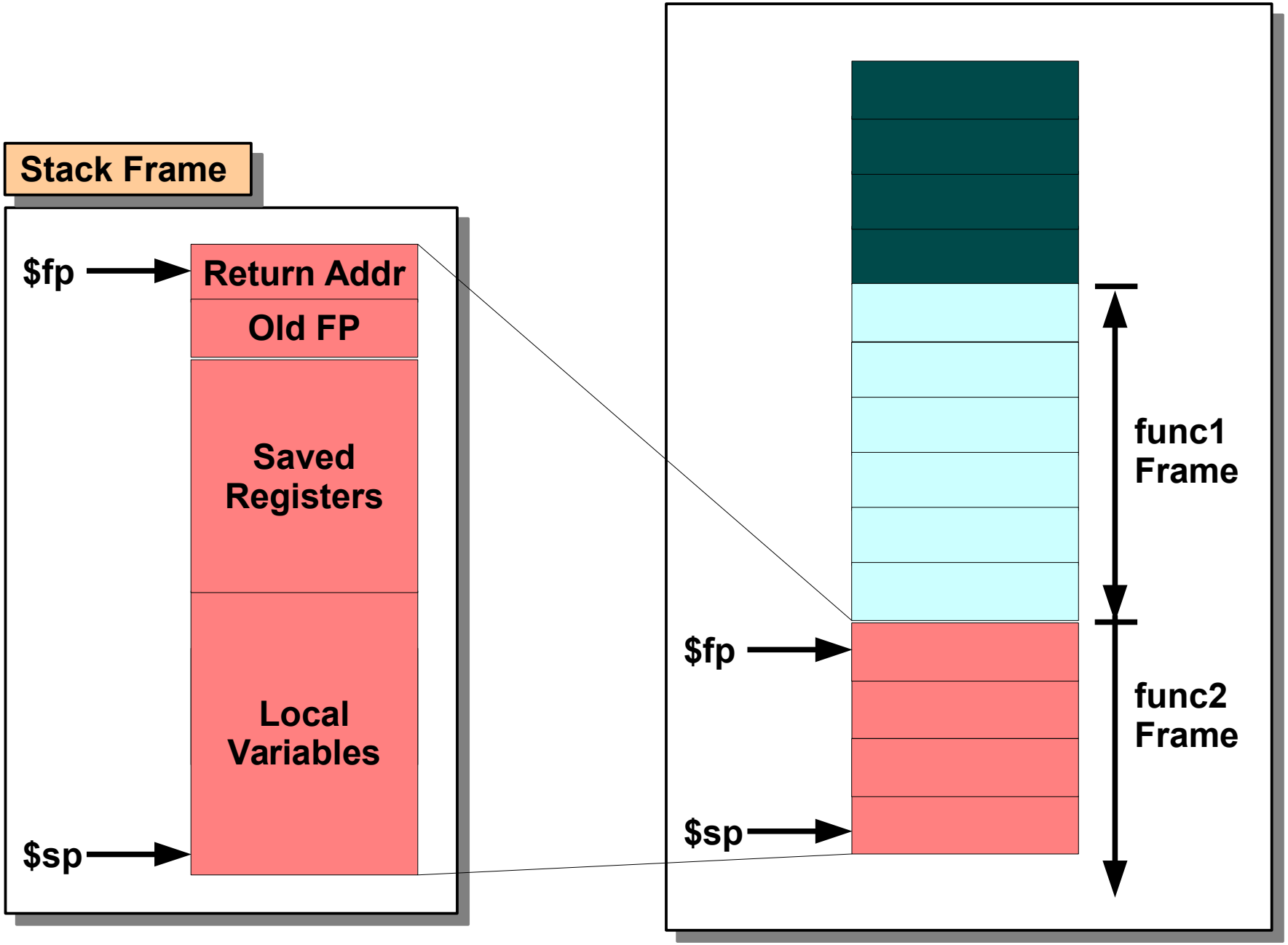
Linking Multiple Modules



The a.out executable

- What does the a.out file contain?
  - Program “code” (machine instructions)
  - Data values (values, size of arrays)
- Other information that is needed for
  - execution
  - debugging
    - Debugging: The stage in program development where mistakes (“bugs”) in the program are identified

Stack Frame – Recall



Saved Registers

- Registers 16 – 23 are saved across function calls

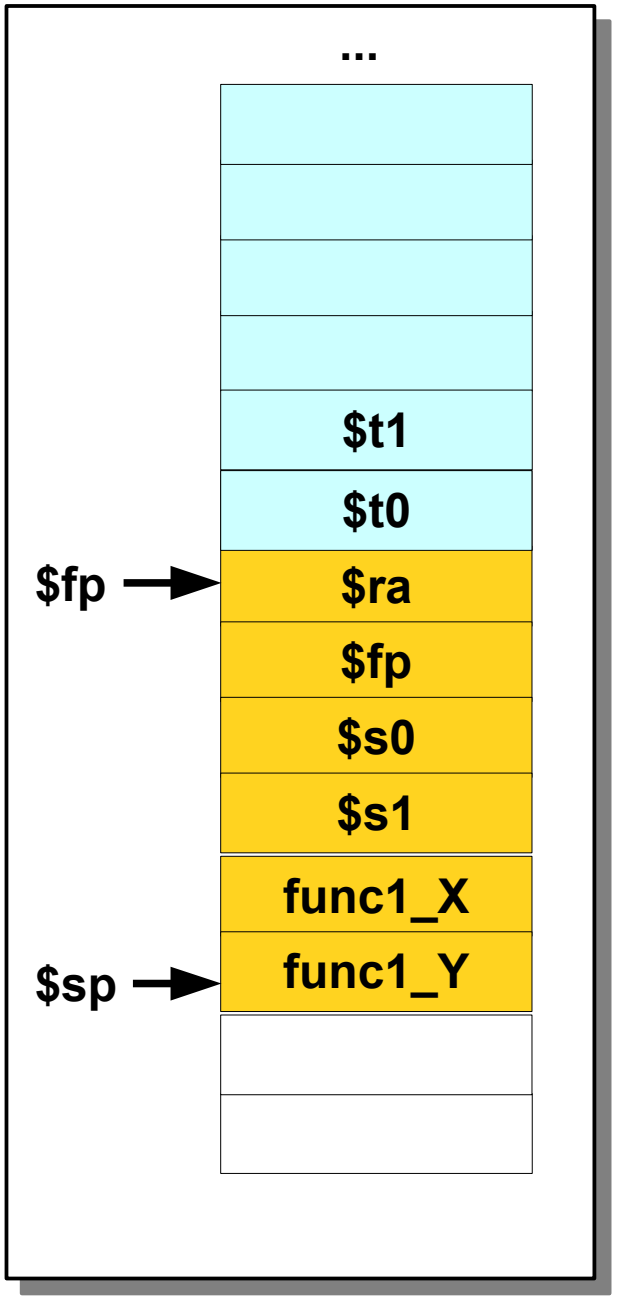
Name	Register number	Usage	Preserved on call?
$zero	0	The constant value 0	n.a.
$v0–$v1	2–3	Values for results and expression evaluation	no
$a0–$a3	4–7	Arguments	no
$t0–$t7	8–15	Temporaries	no
$s0–$s7	16–23	Saved	yes
$t8–$t9	24–25	More temporaries	no
$gp	28	Global pointer	yes
$sp	29	Stack pointer	yes
$fp	30	Frame pointer	yes
$ra	31	Return address	yes

Saved Registers

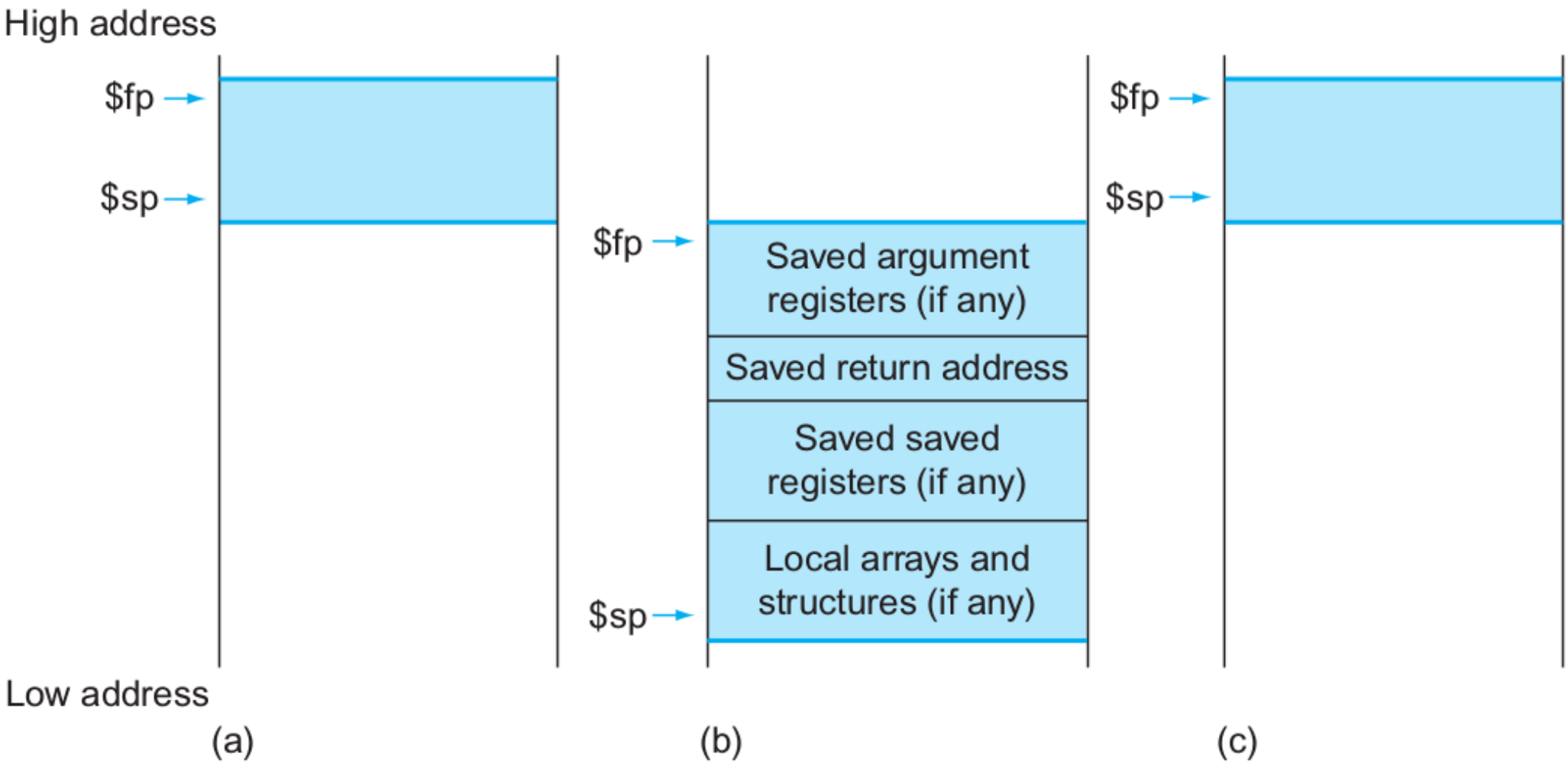
- Registers 16 – 23 are saved across function calls
- Save registers $s0 - $s7 if used by the callee
- Example: $s0, $s1 are saved

Stack Frame

- Local variables are allocated on the stack after the saved registers



Stack Frame


High address
$fp
$sp
Low address
(a)
$fp
Saved argument registers (if any)
Saved return address
Saved saved registers (if any)
Local arrays and structures (if any)
$sp
(b)
$fp
$sp
(c)