INSTRUCTIONS: LANGUAGE OF THE COMPUTER

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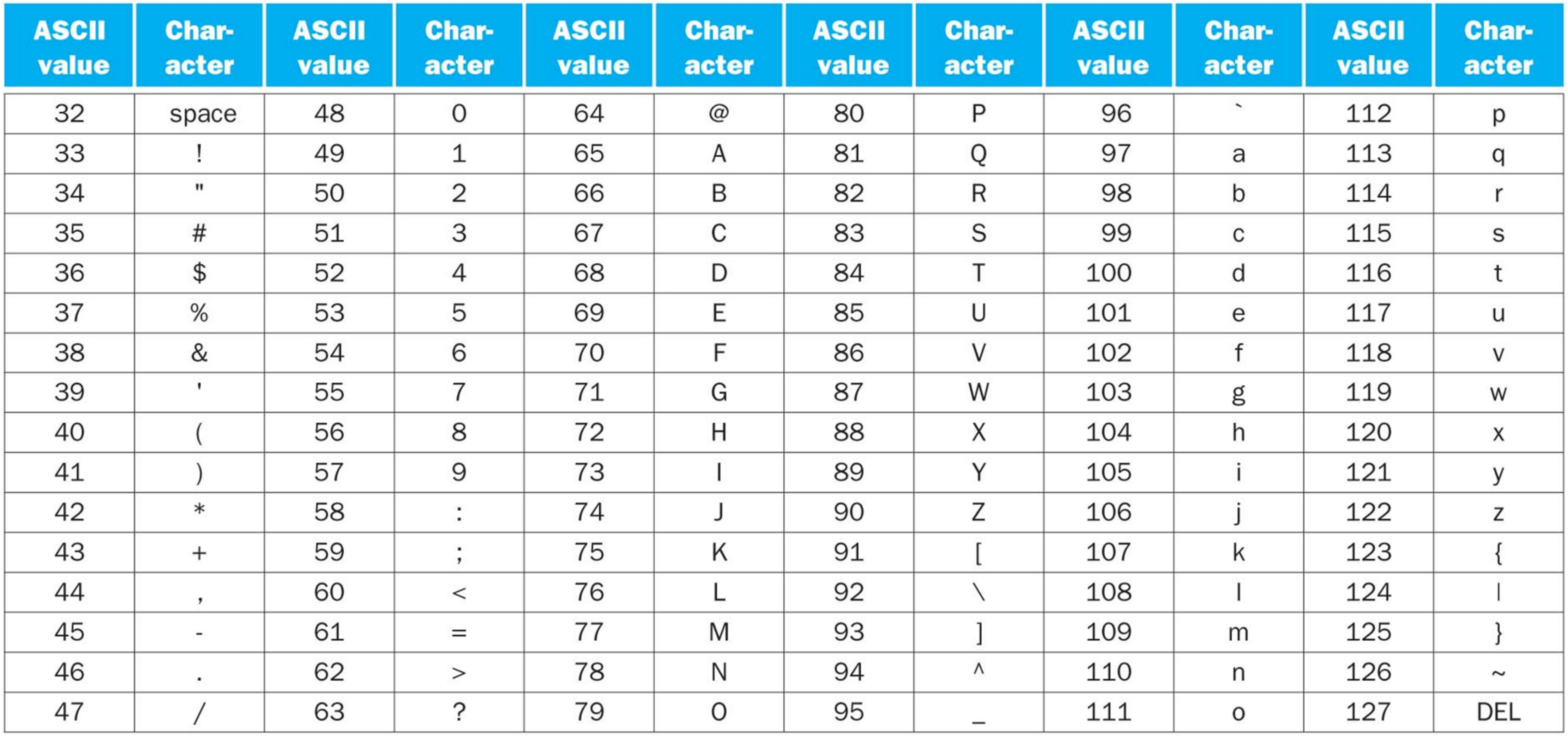
§2.9 Communicating with People

Communicating with People

- Byte-encoded character sets
  - ASCII: 128 characters
    - 95 graphic, 33 control
  - Latin-1: 256 characters

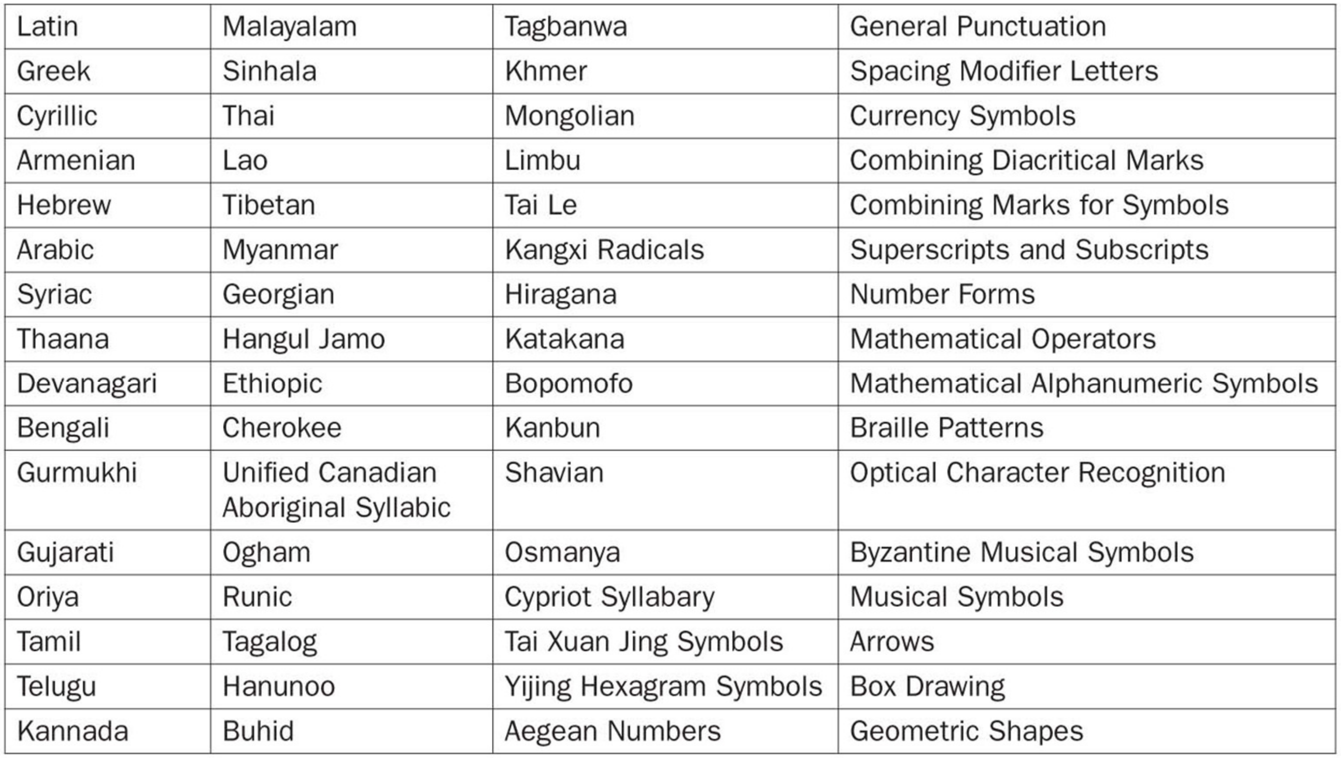


ASCII value	Char-acter	ASCII value	Char-acter	ASCII value	Char-acter	ASCII value	Char-acter	ASCII value	Char-acter	ASCII value	Char-acter
32	space	48	0	64	@	80	P	96	`	112	p
33	!	49	1	65	A	81	Q	97	a	113	q
34	"	50	2	66	B	82	R	98	b	114	r
35	#	51	3	67	C	83	S	99	c	115	s
36	$	52	4	68	D	84	T	100	d	116	t
37	%	53	5	69	E	85	U	101	e	117	u
38	&	54	6	70	F	86	V	102	f	118	v
39	'	55	7	71	G	87	W	103	g	119	w
40	(	56	8	72	H	88	X	104	h	120	x
41	)	57	9	73	I	89	Y	105	i	121	y
42	*	58	:	74	J	90	Z	106	j	122	z
43	+	59	;	75	K	91	[	107	k	123	{
44	,	60	<	76	L	92	\	108	l	124	|
45	-	61	=	77	M	93	]	109	m	125	}
46	.	62	>	78	N	94	^	110	n	126	~
47	/	63	?	79	O	95	_	111	o	127	DEL

§2.9 Communicating with People

Character Data

- Unicode: 32-bit character set
  - Used in Java, C++ wide characters, …
  - Most of the world’s alphabets, plus symbols
  - UTF-8, UTF-16: variable-length encodings



Latin	Malayalam	Tagbanwa	General Punctuation
Greek	Sinhala	Khmer	Spacing Modifier Letters
Cyrillic	Thai	Mongolian	Currency Symbols
Armenian	Lao	Limbu	Combining Diacritical Marks
Hebrew	Tibetan	Tai Le	Combining Marks for Symbols
Arabic	Myanmar	Kangxi Radicals	Superscripts and Subscripts
Syriac	Georgian	Hiragana	Number Forms
Thaana	Hangul Jamo	Katakana	Mathematical Operators
Devanagari	Ethiopic	Bopomofo	Mathematical Alphanumeric Symbols
Bengali	Cherokee	Kanbun	Braille Patterns
Gurmukhi	Unified Canadian Aboriginal Syllabic	Shavian	Optical Character Recognition
Gujarati	Ogham	Osmanya	Byzantine Musical Symbols
Oriya	Runic	Cypriot Syllabary	Musical Symbols
Tamil	Tagalog	Tai Xuan Jing Symbols	Arrows
Telugu	Hanunoo	Yijing Hexagram Symbols	Box Drawing
Kannada	Buhid	Aegean Numbers	Geometric Shapes

Byte/Halfword Operations

- Could use bitwise operations
- MIPS byte/halfword load/store
  - String processing is a common case

```
lb rt, offset(rs)      lh rt, offset(rs)
```

- Sign extend to 32 bits in rt

```
lbu rt, offset(rs)     lhu rt, offset(rs)
```

- Zero extend to 32 bits in rt

```
sb rt, offset(rs)      sh rt, offset(rs)
```

- Store just rightmost byte/halfword

String Copy Example

- C code (naïve):
  - Null-terminated string

```
void strcpy (char x[], char y[])
{ int i;
  i = 0;
  while ((x[i]=y[i])!='\0')
    i += 1;
}
```

  - Addresses of x, y in $a0, $a1
  - i in $s0

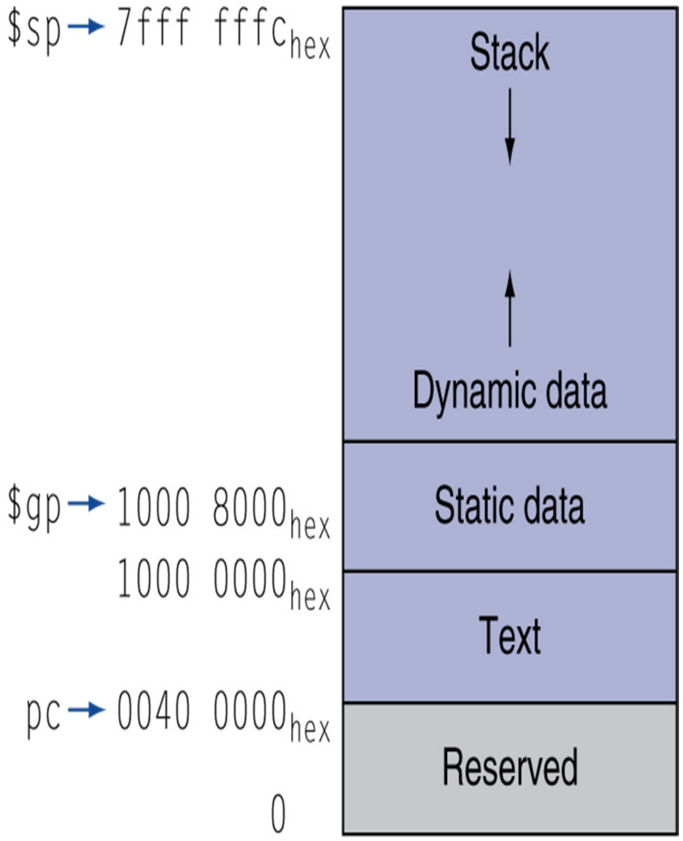
String Copy Example

- MIPS code:

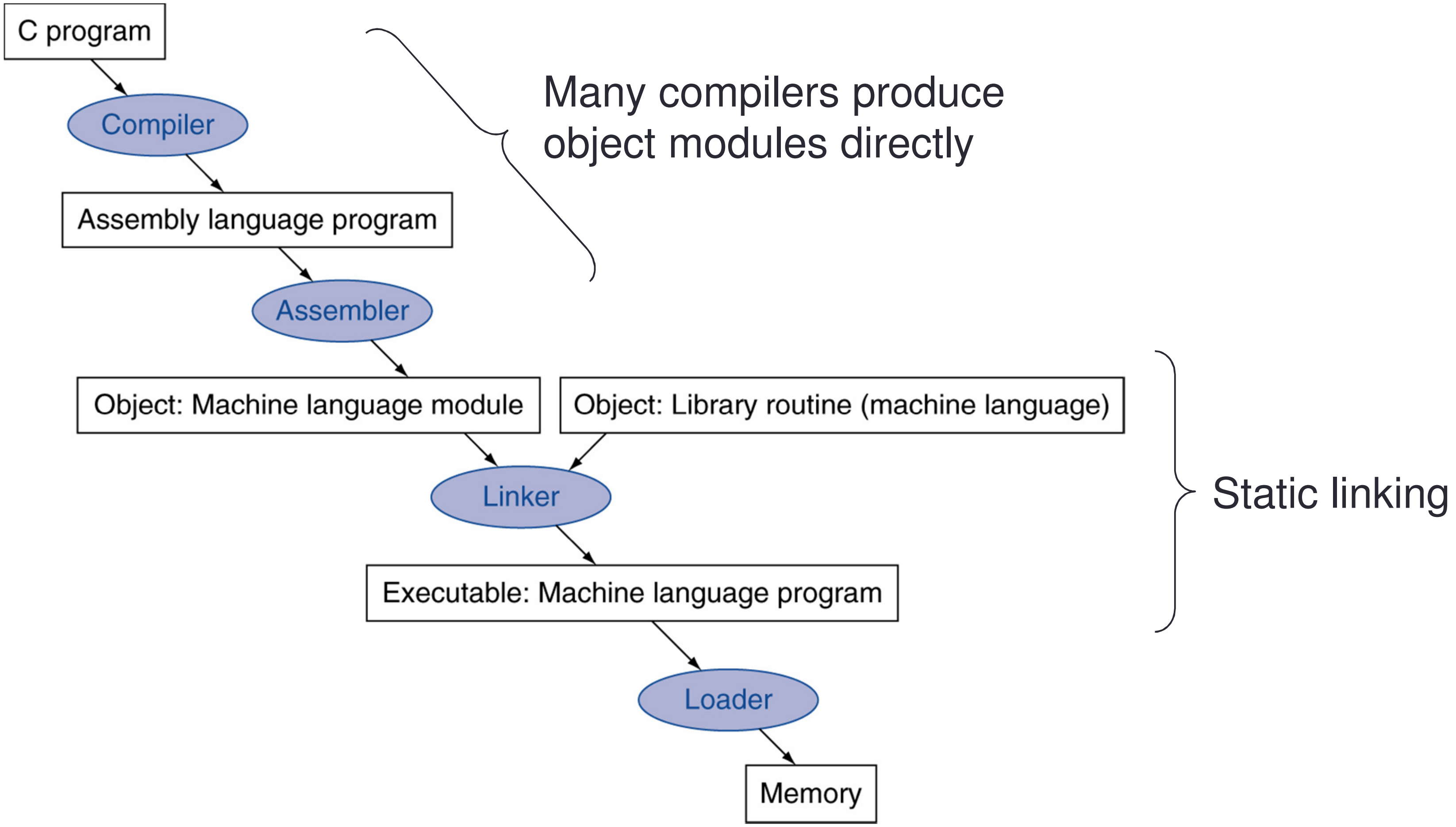
```
strcpy:
    addi $sp, $sp, -4      # adjust stack for 1 item
    sw   $s0, 0($sp)       # save $s0
    add  $s0, $zero, $zero # i = 0
L1: add  $t1, $s0, $a1     # addr of y[i] in $t1
    lbu  $t2, 0($t1)       # $t2 = y[i]
    add  $t3, $s0, $a0     # addr of x[i] in $t3
    sb   $t2, 0($t3)       # x[i] = y[i]
    beq  $t2, $zero, L2    # exit loop if y[i] == 0
    addi $s0, $s0, 1       # i = i + 1
    j    L1                # next iteration of loop
L2: lw   $s0, 0($sp)       # restore saved $s0
    addi $sp, $sp, 4       # pop 1 item from stack
    jr   $ra               # and return
```

Memory Map

- Text: program code
- Static data: global variables
  - e.g., static variables in C, constant arrays and strings
  - $gp initialized to address allowing ±offsets into this segment
- Dynamic data: heap
  - E.g., malloc in C, new in Java
- Stack: automatic storage



Translation and Startup


C program
Compiler
Assembly language program
Assembler
Object: Machine language module
Object: Library routine (machine language)
Linker
Executable: Machine language program
Loader
Memory

Many compilers produce object modules directly

Static linking

Assembler Pseudoinstructions

- Most assembler instructions represent machine instructions one-to-one
- Pseudoinstructions: figments of the assembler's imagination

```
move $t0, $t1      →  add $t0, $zero, $t1
blt $t0, $t1, L    →  slt $at, $t0, $t1
                      bne $at, $zero, L
```

  - $at (register 1): assembler temporary

Producing an Object Module

- 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, labels and external refs
  - Debug info: for associating with source code

Linking Object Modules

- Produces an executable image
  1. Merges segments
  2. Resolve labels (determine their addresses)
  3. Patch location-dependent and external refs
- Could leave location dependencies for fixing by a relocating loader
  - But with virtual memory, no need to do this
  - Program can be loaded into absolute location in virtual memory space

Loading a Program

- Load from image file on disk into memory

1. Read header to determine segment sizes
2. Create address space enough for text (instructions) and data
3. Copy text and initialized data into memory
    - Or set page table entries so they can be faulted in
4. Set up arguments on stack (copy)
5. Initialize registers (including $sp, $fp, $gp)
6. Jump to startup routine
    - Copies arguments to $a0, … and calls main
    - When main returns, do exit syscall

Example Program: C Code

```
int f, g, y;  // global variables
int main(void)
{
  f = 2;
  g = 3;
  y = sum(f, g);
  return y;
}
int sum(int a, int b) {
  return (a + b);
}
```

Example Program: Compilation

```
int f, g, y;  // global


int main(void)
{


  f = 2;
  g = 3;

  y = sum(f, g);
  return y;
}

int sum(int a, int b) {
  return (a + b);
}
```

```
.data
f:
g:
y:
.text
main:
  addi $sp, $sp, -4   # stack frame
  sw   $ra, 0($sp)    # store $ra
  addi $a0, $0, 2     # $a0 = 2
  sw   $a0, f         # f = 2
  addi $a1, $0, 3     # $a1 = 3
  sw   $a1, g         # g = 3
  jal  sum            # call sum
  sw   $v0, y         # y = sum()
  lw   $ra, 0($sp)    # restore $ra
  addi $sp, $sp, 4    # restore $sp
  jr   $ra            # return to OS
sum:
  add  $v0, $a0, $a1  # $v0 = a + b
  jr   $ra            # return
```

Assembling

- Assembly language to code (1,0)
- Two steps
  - First:
  - Assign Instruction addresses
  - Finds Symbols (Labels and Global variable names)
    - Symbol table (determine addresses)
  - Second:
  - Machine language code
  - Use the symbol table

Example Program: Symbol Table

Symbol	Address
f	0x10000000
g	0x10000004
y	0x10000008
main	0x00400000
sum	0x0040002C

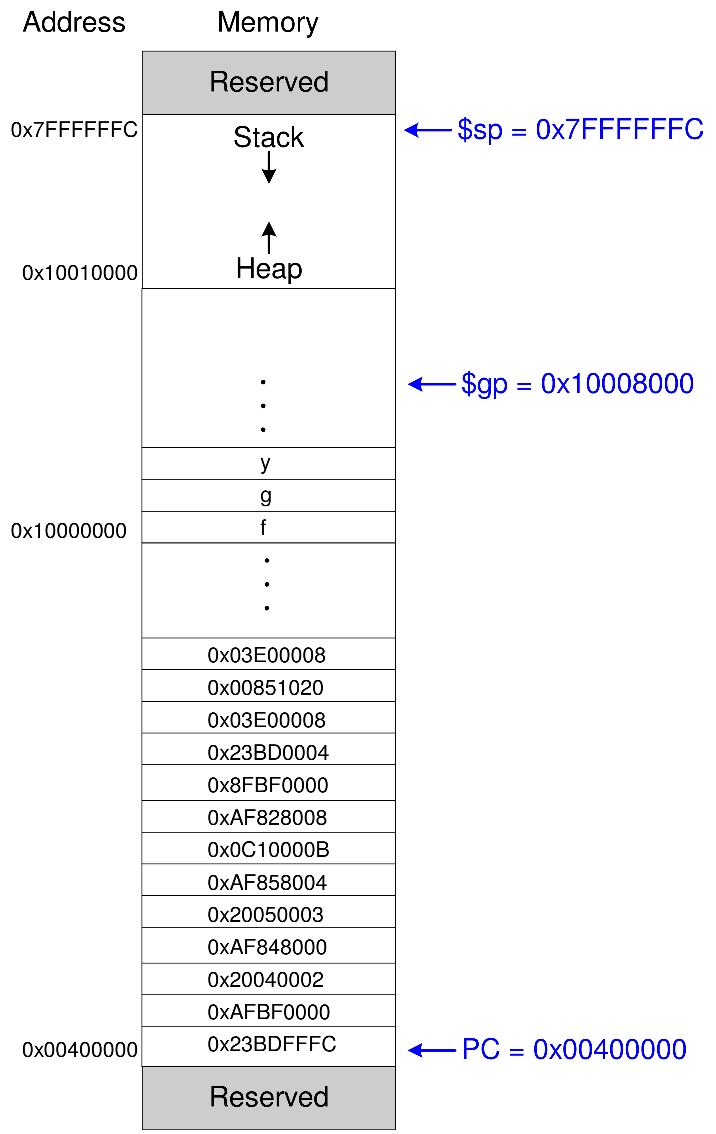
Example Program: Executable

Executable file header	Text Size	Data Size
	0x34 (52 bytes)	0xC (12 bytes)

Text segment	Address	Instruction	
	0x00400000	0x23BDFFFC	addi $sp, $sp, -4
	0x00400004	0xAFBF0000	sw $ra, 0 ($sp)
	0x00400008	0x20040002	addi $a0, $0, 2
	0x0040000C	0xAF848000	sw $a0, 0x8000 ($gp)
	0x00400010	0x20050003	addi $a1, $0, 3
	0x00400014	0xAF858004	sw $a1, 0x8004 ($gp)
	0x00400018	0x0C10000B	jal 0x0040002C
	0x0040001C	0xAF828008	sw $v0, 0x8008 ($gp)
	0x00400020	0x8FBF0000	lw $ra, 0 ($sp)
	0x00400024	0x23BD0004	addi $sp, $sp, -4
	0x00400028	0x03E00008	jr $ra
	0x0040002C	0x00851020	add $v0, $a0, $a1
	0x00400030	0x03E0008	jr $ra

Data segment	Address	Data
	0x10000000	f
	0x10000004	g
	0x10000008	y

Example Program: In Memory



Address	Memory	
	Reserved	
0x7FFFFFFC	Stack ↓	← $sp = 0x7FFFFFFC
0x10010000	↑ Heap	
	. . .	← $gp = 0x10008000
	y	
	g	
0x10000000	f	
	. . .	
	0x03E00008	
	0x00851020	
	0x03E00008	
	0x23BD0004	
	0x8FBF0000	
	0xAF828008	
	0x0C10000B	
	0xAF858004	
	0x20050003	
	0xAF848000	
	0x20040002	
	0xAFBF0000	
0x00400000	0x23BDFFFC	← PC = 0x00400000
	Reserved	

Dynamic Linking

- Only link/load library procedure when it is called
  - Requires procedure code to be relocatable
  - Avoids image bloat caused by static linking of all (transitively) referenced libraries
  - Automatically picks up new library versions

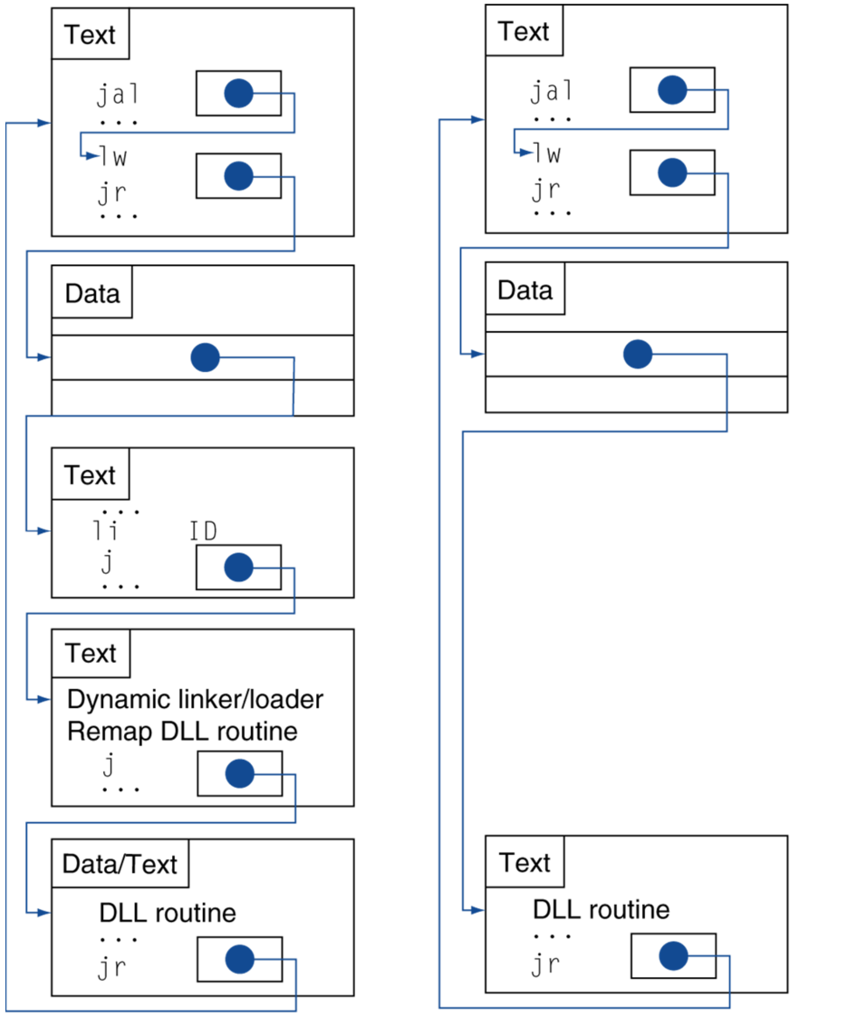
Lazy Linkage

Indirection table

Stub: Loads routine ID, Jump to linker/loader

Linker/loader code

Dynamically mapped code



a. First call to DLL routine

b. Subsequent calls to DLL routine