Compilation

0368-3133

Lecture 12

Assemblers, linkers, loaders

Noam Rinetzky

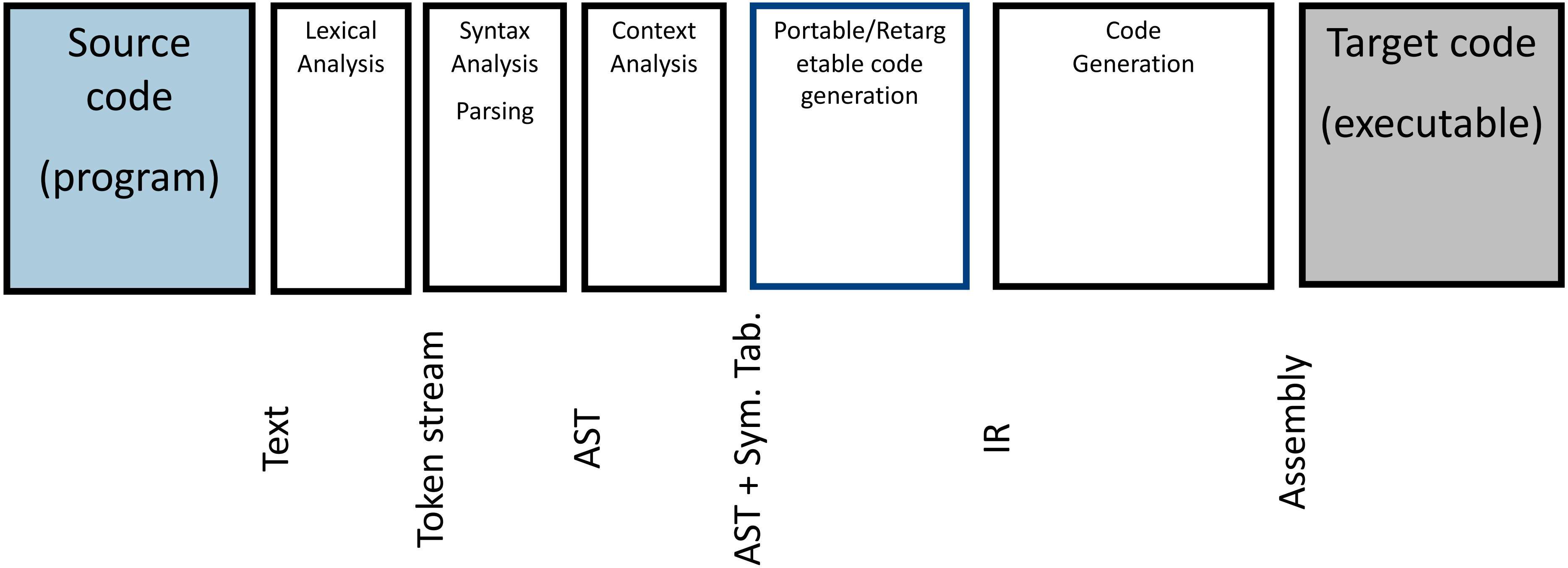
What is a compiler?

“A compiler is a computer program that transforms source code written in a programming language (source language) into another language (target language).

The most common reason for wanting to transform source code is to create an executable program.”

--Wikipedia

Stages of compilation



Source code

(program)

Lexical Analysis

Syntax Analysis

Parsing

Context Analysis

Portable/Retargetable code generation

Code Generation

Target code

(executable)

Text

Token stream

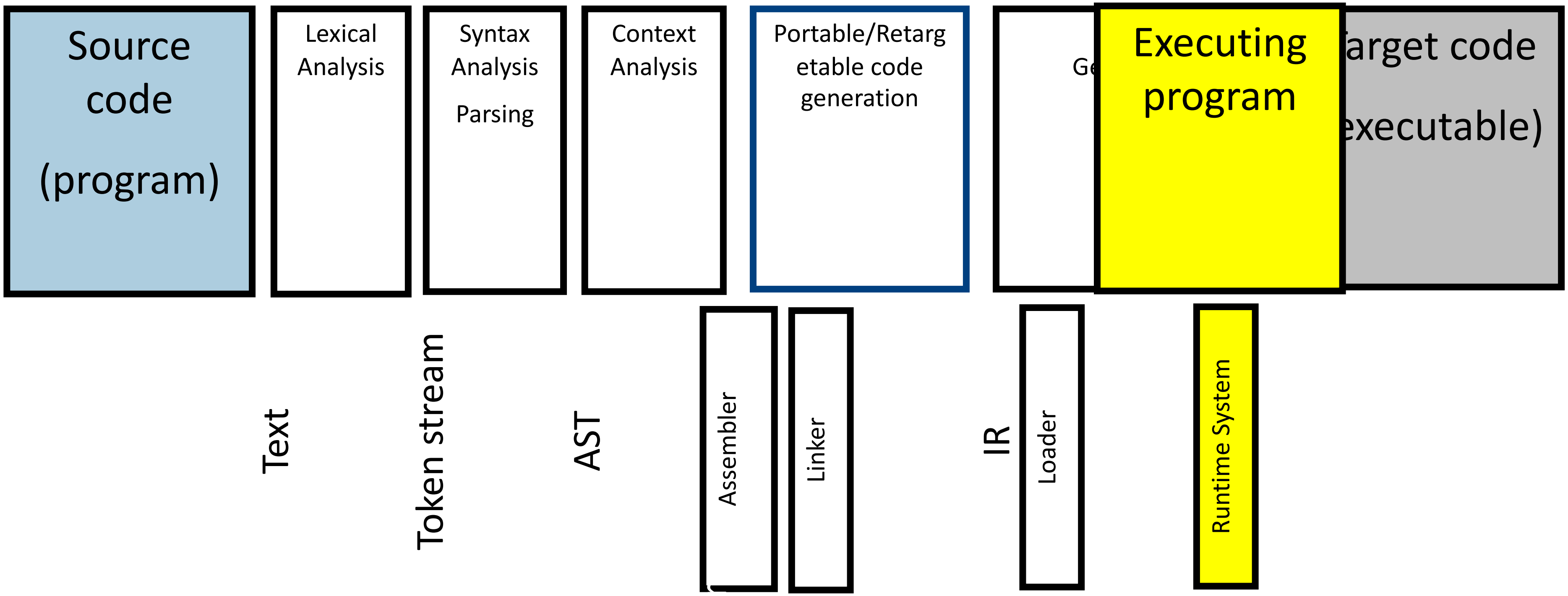
AST

AST + Sym. Tab.

IR

Assembly

Compilation → Execution



Source code

(program)

Lexical Analysis

Syntax Analysis

Parsing

Context Analysis

Portable/Retargetable code generation

Ge

Executing program

arget code

executable)

Text

Token stream

AST

Assembler

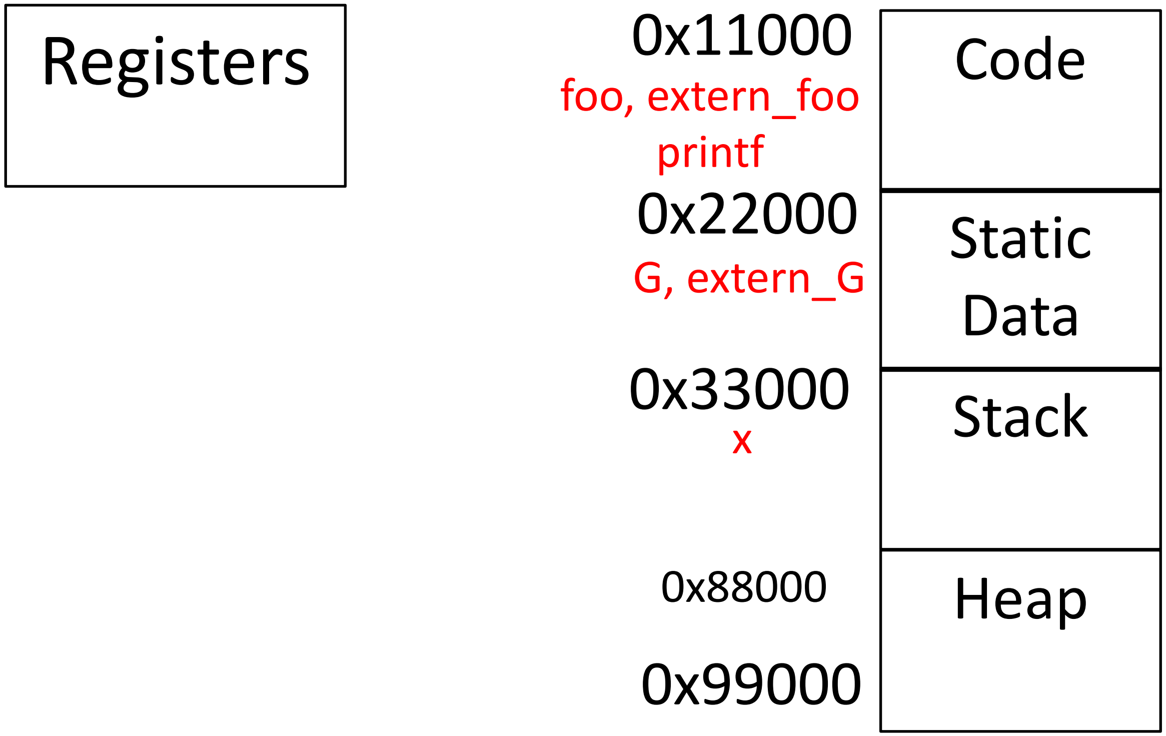
Linker

IR

Loader

Runtime System

Program Runtime State



Registers

0x11000

foo, extern_foo

printf

Code

0x22000

G, extern_G

Static Data

0x33000

x

Stack

0x88000

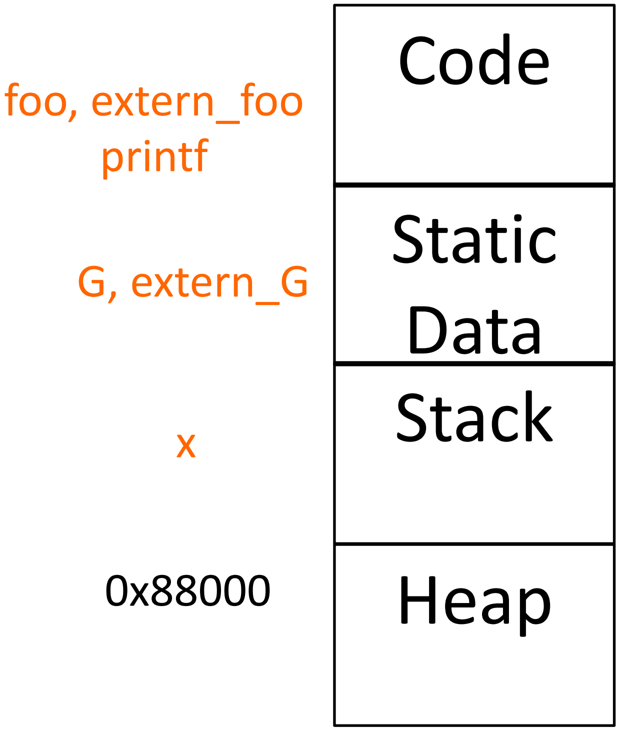
Heap

0x99000

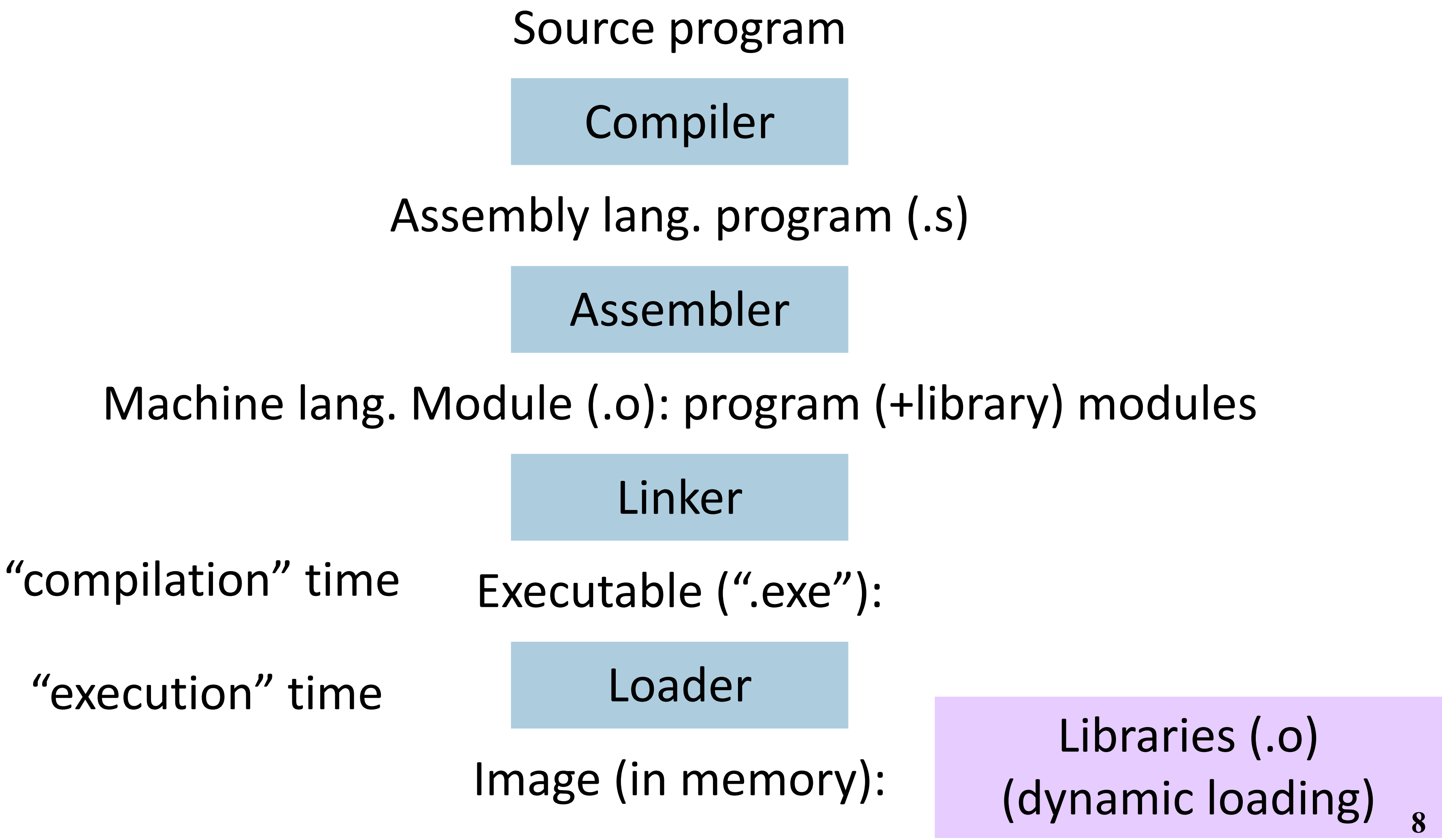
Challenges

- goto L2 → JMP 0x110FF
- G:=3 → MOV 0x2200F, 0..011
- foo() → CALL 0x130FF
- extern_G := 1 → MOV 0x2400F, 0..01
- extern_foo() → CALL 0x140FF
- printf() → CALL 0x150FF

- x:=2 → MOV FP+32, 0...010
- goto L2 → JMP [PC +] 0x000FF



Assembly → Image



Source program

Compiler

Assembly lang. program (.s)

Assembler

Machine lang. Module (.o): program (+library) modules

Linker

“compilation” time

Executable (“.exe”):

“execution” time

Loader

Image (in memory):

Libraries (.o)
(dynamic loading)

Assembly → Image

Source file (*e.g., utils*)

Compiler

Assembly (.s)

Assembler

Object (.o)

Source file (*e.g., main*)

Compiler

Assembly (.s)

Assembler

Object (.o)

library

Compiler

Assembly (.s)

Assembler

Object (.o)

Linker

Executable (“.elf”)

Loader

Image (in memory):

Outline

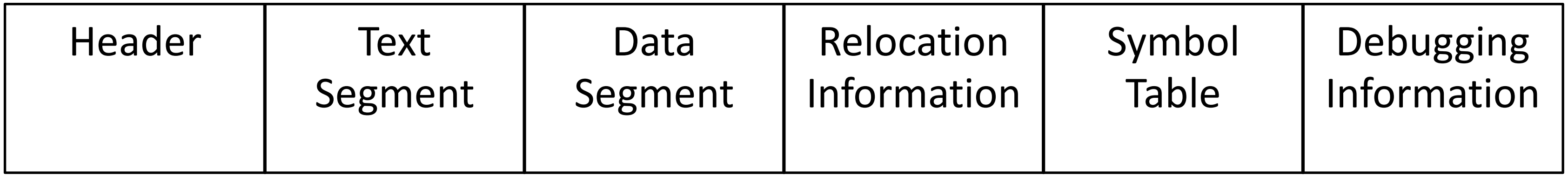
- Assembly
- Linker / Link editor
- Loader

- Static linking
- Dynamic linking

Assembler

- Converts (symbolic) assembler to binary (object) code
    - Object files contain a combination of machine instructions, data, and information needed to place instructions properly in memory
  - Yet another(simple) compiler
    - One-to one translation
- Converts constants to machine repr. (3→0…011)
- Resolve internal references
- Records info for code & data relocation

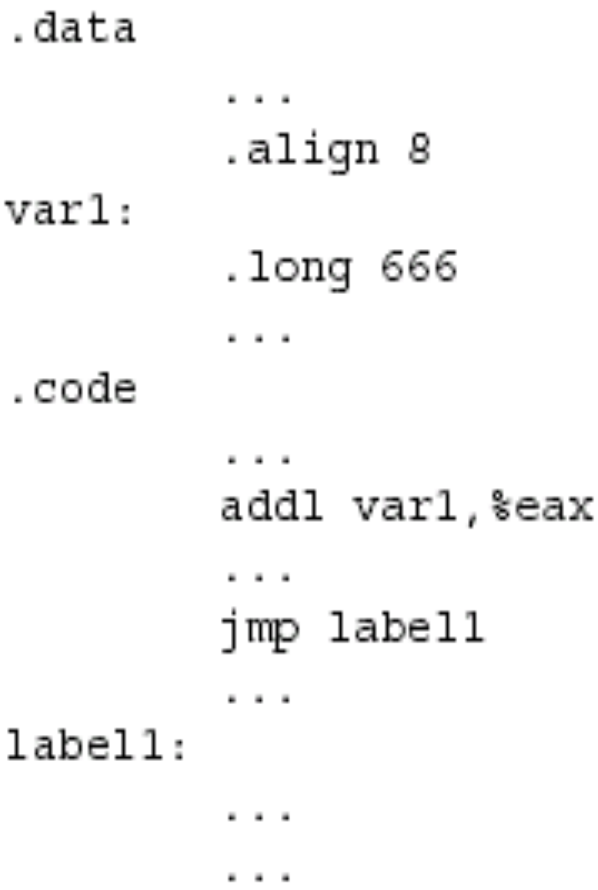
Object File Format



Header | Text Segment | Data Segment | Relocation Information | Symbol Table | Debugging Information

- Header: Admin info + “file map”
- Text seg.: machine instruction
- Data seg.: (Initialized) data in machine format
- Relocation info: instructions and data that depend on absolute addresses
- Symbol table: “exported” references + unresolved references

Handling Internal Addresses



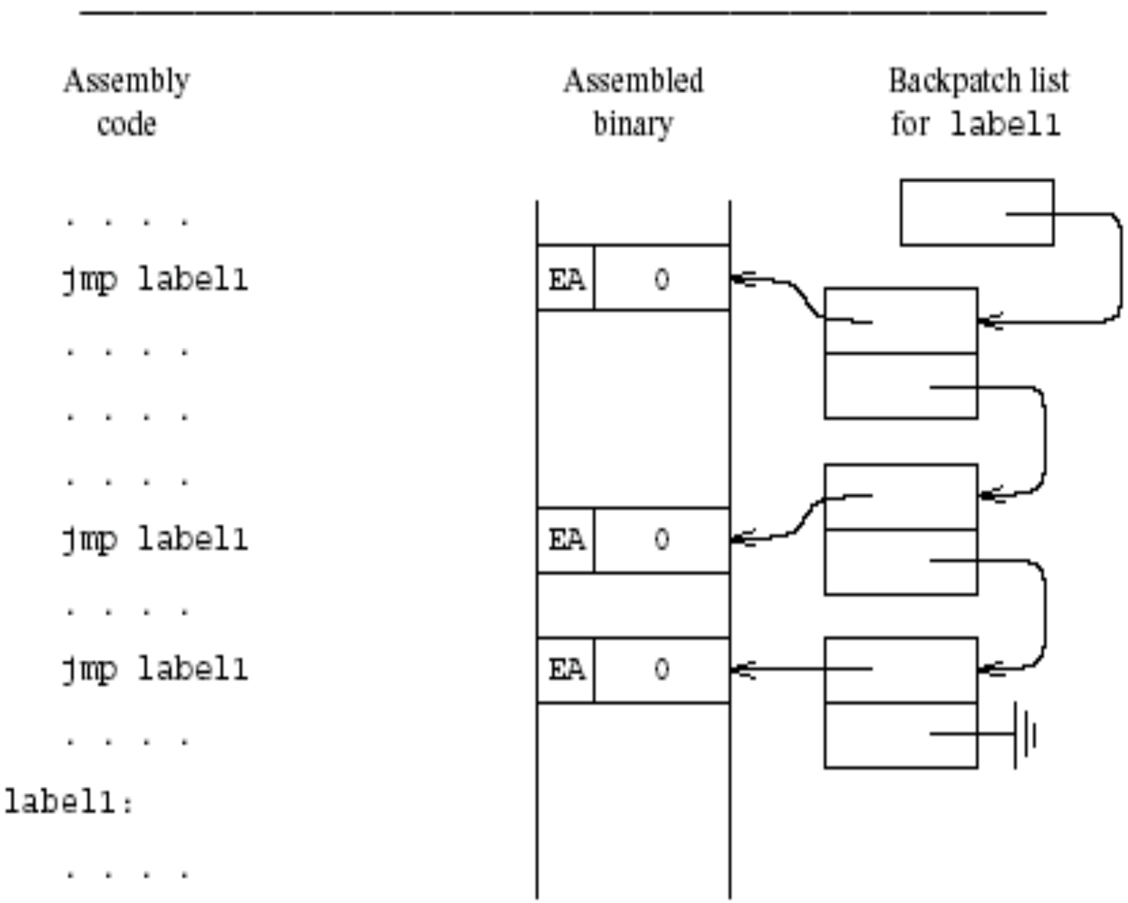
```
.data
        ...
        .align 8
var1:
        .long 666
        ...
.code
        ...
        addl var1,%eax
        ...
        jmp label1
        ...
label1:
        ...
        ...
```

Resolving Internal Addresses

- Two scans of the code
  - Construct a table label → address
  - Replace labels with values

- One scan of the code (Backpatching)
  - Simultaneously construct the table and resolve symbolic addresses
    - Maintains list of unresolved labels
  - Useful beyond assemblers

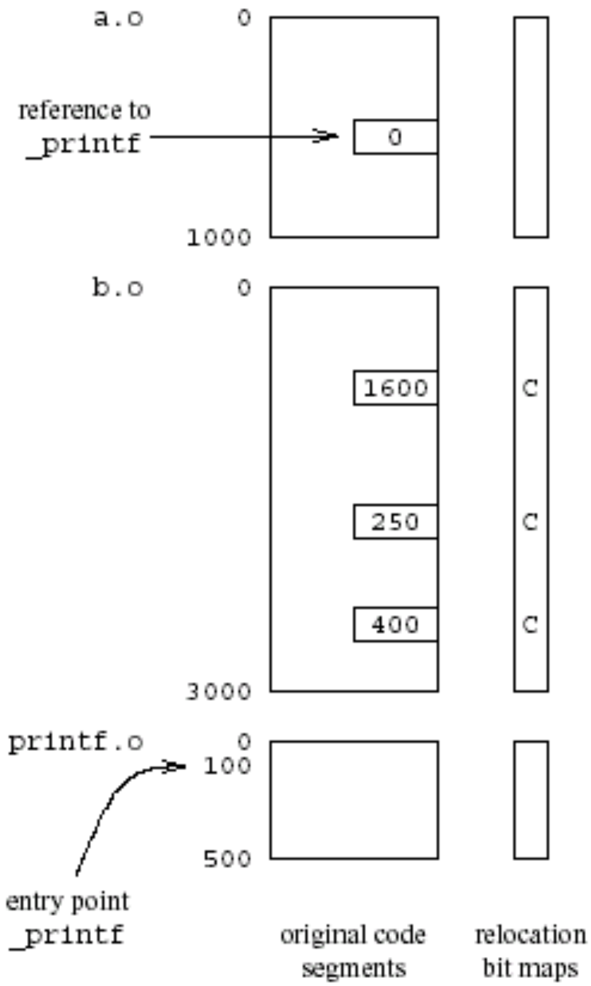
Backpatching



Handling External Addresses

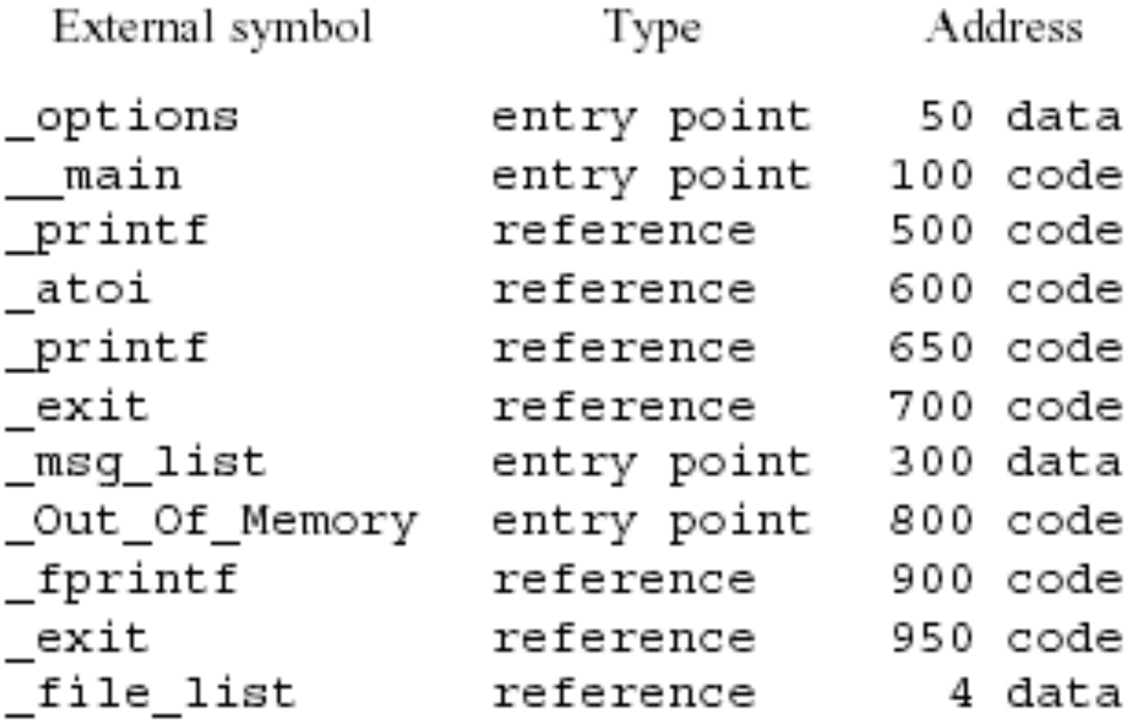
- Record symbol table in “external” table
    - Exported (defined) symbols
        - G, foo()
    - Imported (required) symbols
        - Extern_G, extern_bar(), printf()
- Relocation bits
    - Mark instructions that depend on absolute (fixed) addresses
        - Instructions using globals

Example



External references resolved by the Linker using the relocation info.

Example of External Symbol Table



External symbol	Type	Address
_options	entry point	50 data
__main	entry point	100 code
_printf	reference	500 code
_atoi	reference	600 code
_printf	reference	650 code
_exit	reference	700 code
_msg_list	entry point	300 data
_Out_Of_Memory	entry point	800 code
_fprintf	reference	900 code
_exit	reference	950 code
_file_list	reference	4 data

Assembler Summary

- Converts symbolic machine code to binary
  - addl %edx, %ecx ⇒ 000 0001 11 010 001 = 01 D1 (Hex)
- Format conversions
  - 3 ➔ 0x0..011 or 0x000000110…0
- Resolves internal addresses

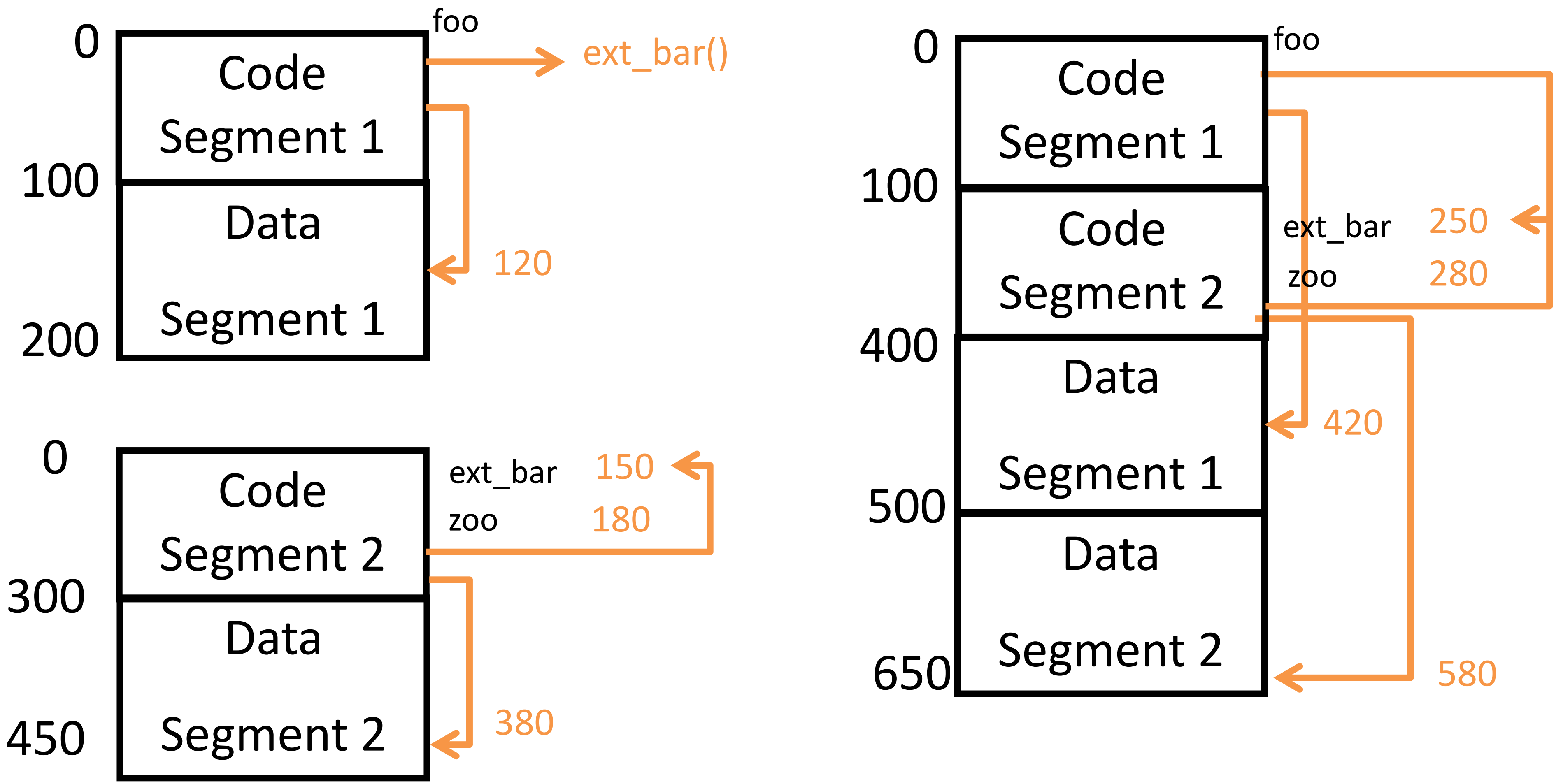
- Some assemblers support overloading
  - Different opcodes based on types

Linker

- Merges object files to an executable
  - Enables separate compilation

- Combine memory layouts of object modules
  - Links program calls to library routines
    - printf(), malloc()
  - Relocates instructions by adjusting absolute references
  - Resolves references among files

Linker



0

Code Segment 1

foo

ext_bar()

100

Data Segment 1

120

200

0

Code Segment 2

ext_bar 150

zoo 180

300

Data Segment 2

380

450

0

Code Segment 1

foo

100

Code Segment 2

ext_bar 250

zoo 280

400

Data Segment 1

420

500

Data Segment 2

580

650

Relocation information

- Information needed to change addresses

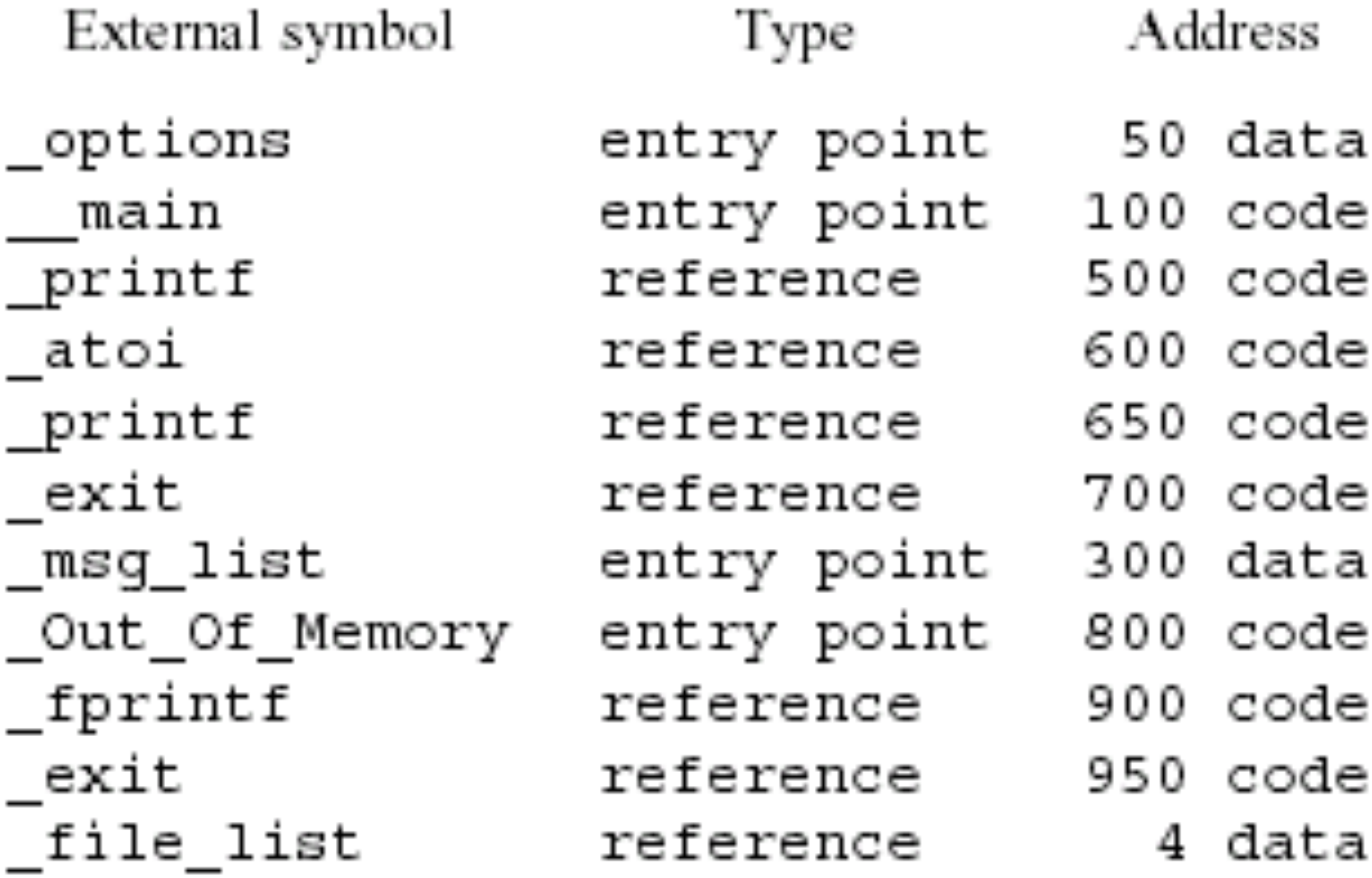
- Positions in the code which contains addresses
  - Data
  - Code

- Two implementations
  - Bitmap
  - Linked-lists

External References

- The code may include references to external names (identifiers)
  - Library calls
  - External data
- Stored in external symbol table

Example of External Symbol Table



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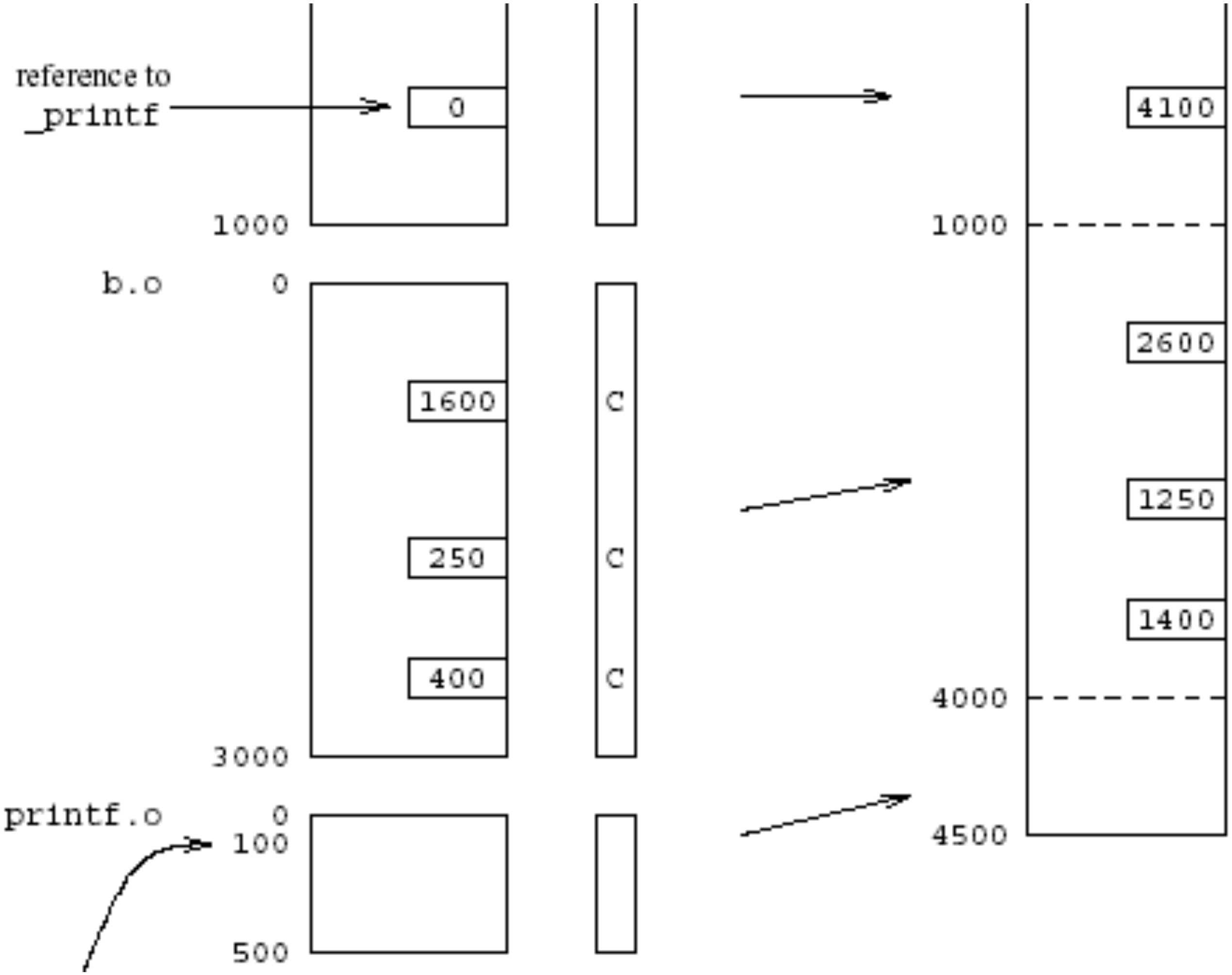
Example


reference to
_printf
0
1000
b.o
0
1600
250
400
C
C
C
3000
printf.o
0
100
500
4100
1000
2600
1250
1400
4000
4500

Linker (Summary)

- Merge several object files
    - Resolve external references
    - Relocate addresses
- User mode
- Provided by the operating system
    - But can be specific for the compiler
        - More secure code
        - Better error diagnosis

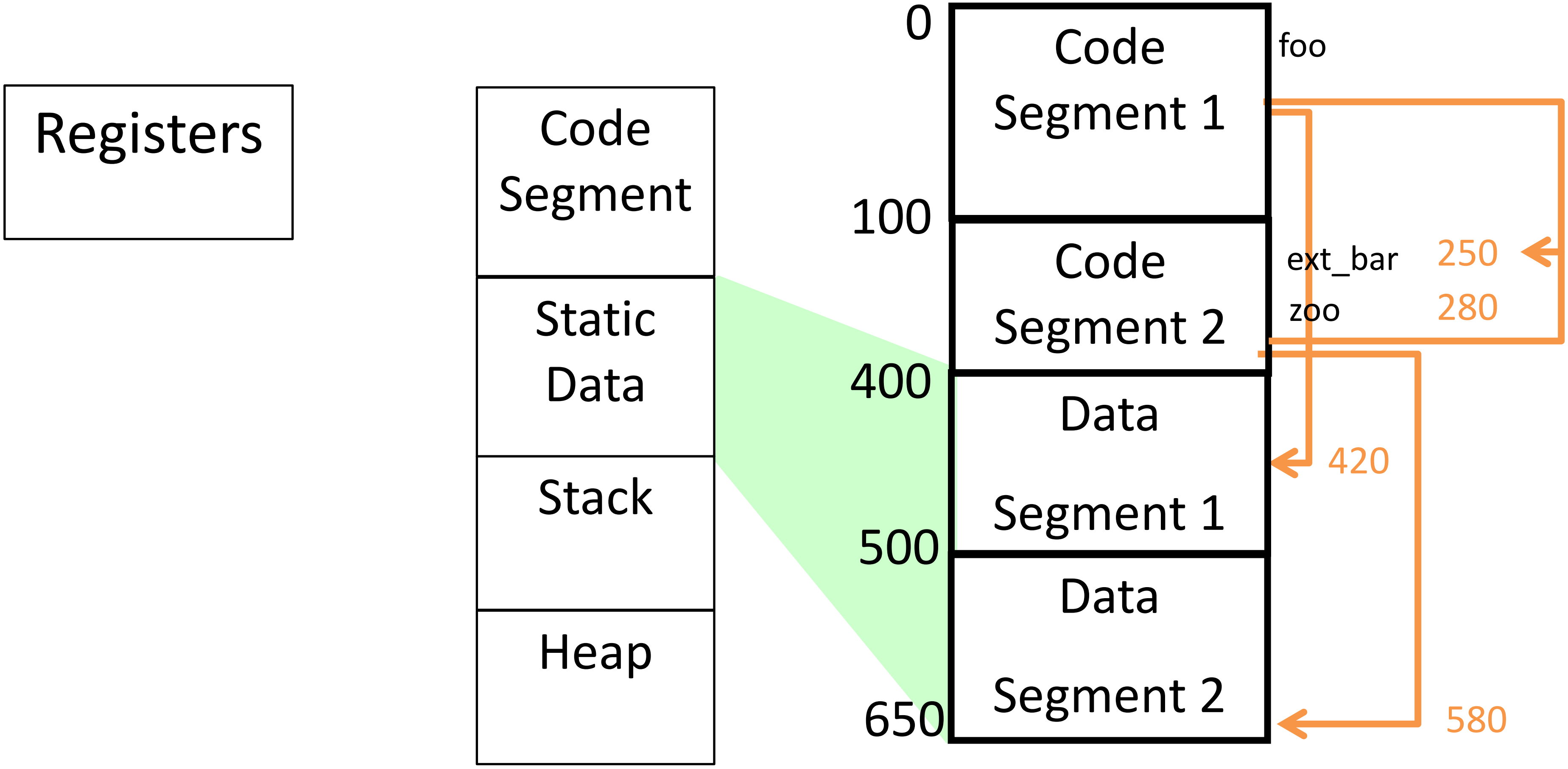
Linker Design Issues

- Merges
  - Code segments
  - Data segments
  - Relocation bit maps
  - External symbol tables
- Retain information about static length
- Real life complications
  - Aggregate initializations
  - Object file formats
  - Large library
  - Efficient search procedures

Loader

- Brings an executable file from disk into memory and starts it running
  - Read executable file's header to determine the size of text and data segments
  - Create a new address space for the program
  - Copies instructions and data into memory
  - Copies arguments passed to the program on the stack
- Initializes the machine registers including the stack ptr
- Jumps to a startup routine that copies the program's arguments from the stack to registers and calls the program's main routine

Program Loading



Loader (Summary)

- Initializes the runtime state
- Part of the operating system
  - Privileged mode
- Does not depend on the programming language
- “Invisible activation record”

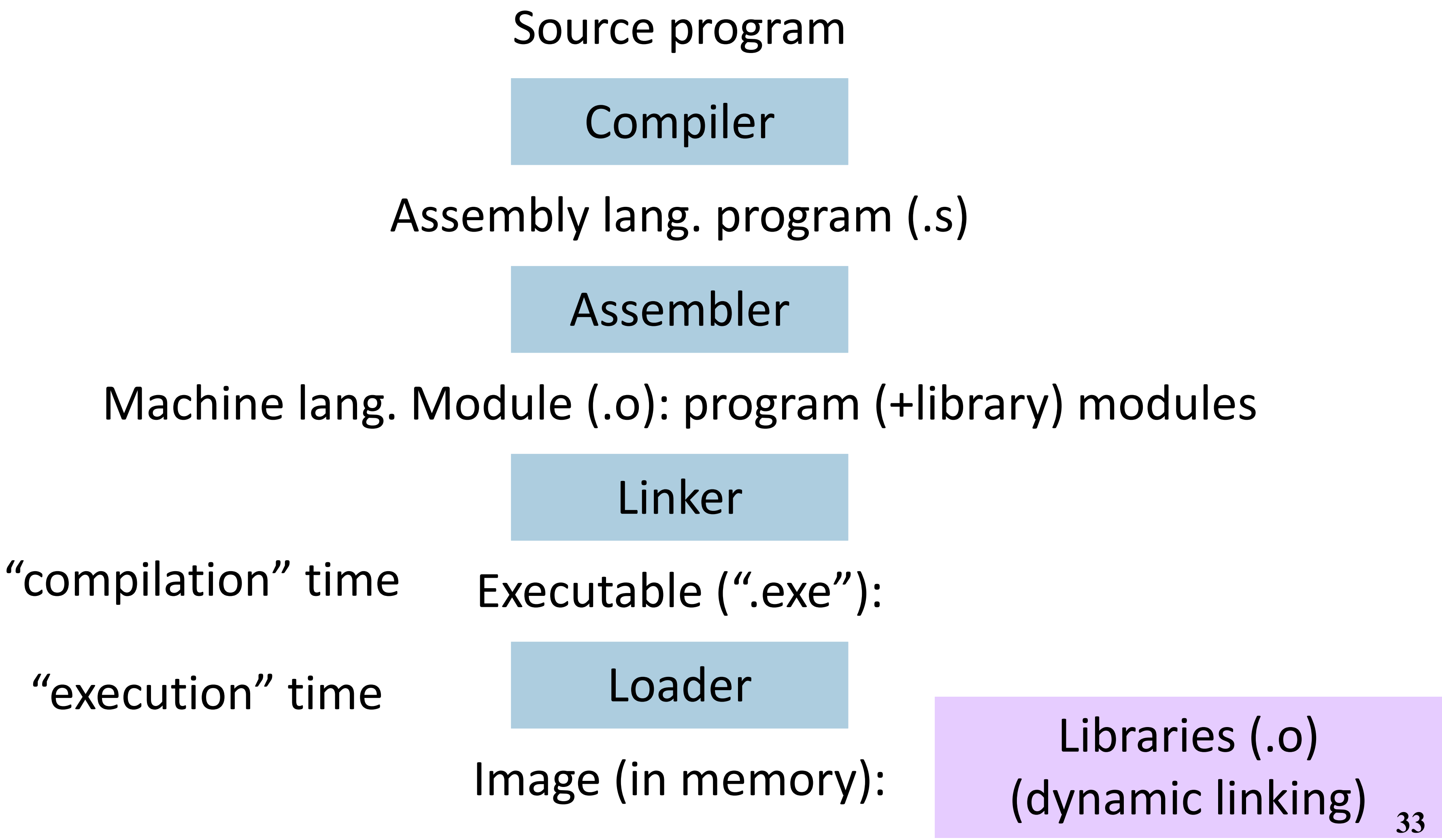
Static Linking (Recap)

- Assembler generates binary code
  - Unresolved addresses
  - Relocatable addresses
- Linker generates executable code
- Loader generates runtime states (images)

Dynamic Linking

- Why dynamic linking?
  - Shared libraries
    - Save space
    - Consistency
  - Dynamic loading
    - Load on demand

What's the challenge?



Source program

Compiler

Assembly lang. program (.s)

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Machine lang. Module (.o): program (+library) modules

Linker

"compilation" time

Executable (".exe"):

"execution" time

Loader

Image (in memory):

Libraries (.o)
(dynamic linking)

Position-Independent Code (PIC)

- Code which does not need to be changed regardless of the address in which it is loaded
  - Enable loading the same object file at different addresses
    - Thus, shared libraries and dynamic loading

- “Good” instructions for PIC: use relative addresses
  - relative jumps
  - reference to activation records

- “Bad” instructions for : use fixed addresses
  - Accessing global and static data
  - Procedure calls
    - Where are the library procedures located?

How?

“All problems in computer science can be solved by another level of indirection"

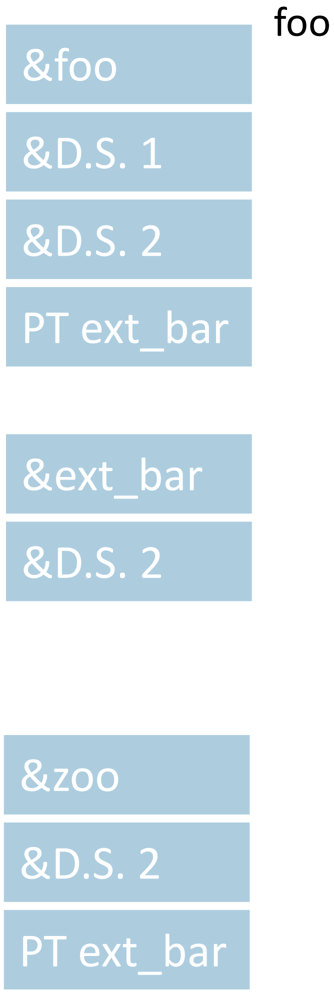
Butler Lampson / David Wheeler

PIC: The Main Idea

- Keep the global data in a table
- Refer to all data relative to the designated register

Per-Routine Pointer Table

- Record for every routine in a table



foo

&foo

&D.S. 1

&D.S. 2

PT ext_bar

&ext_bar

&D.S. 2

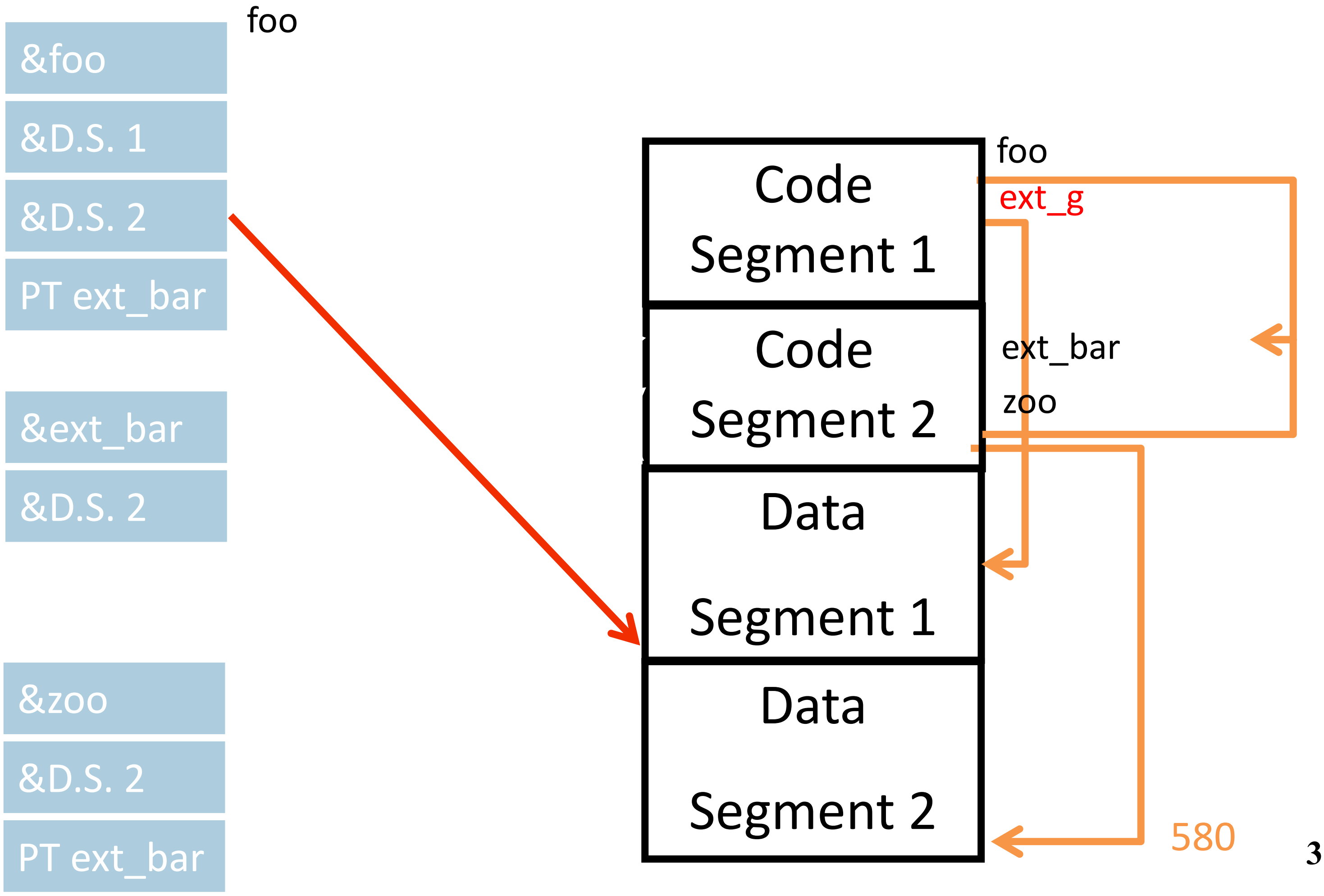
&zoo

&D.S. 2

PT ext_bar

Per-Routine Pointer Table

- Record for every routine in a table



Per-Routine Pointer Table

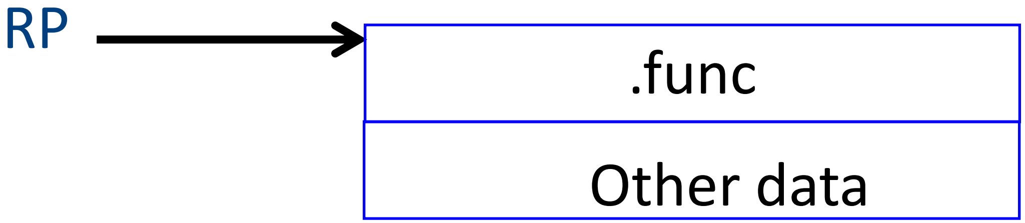
- Record for every routine in a table
- Record used as a address to procedure

Caller:

1. Load Pointer table address into RP
2. Load Code address from 0(RP) into RC
3. Call via RC

Callee:

1. RP points to pointer table
2. Table has addresses of pointer table for sub-procedures



RP

.func

Other data

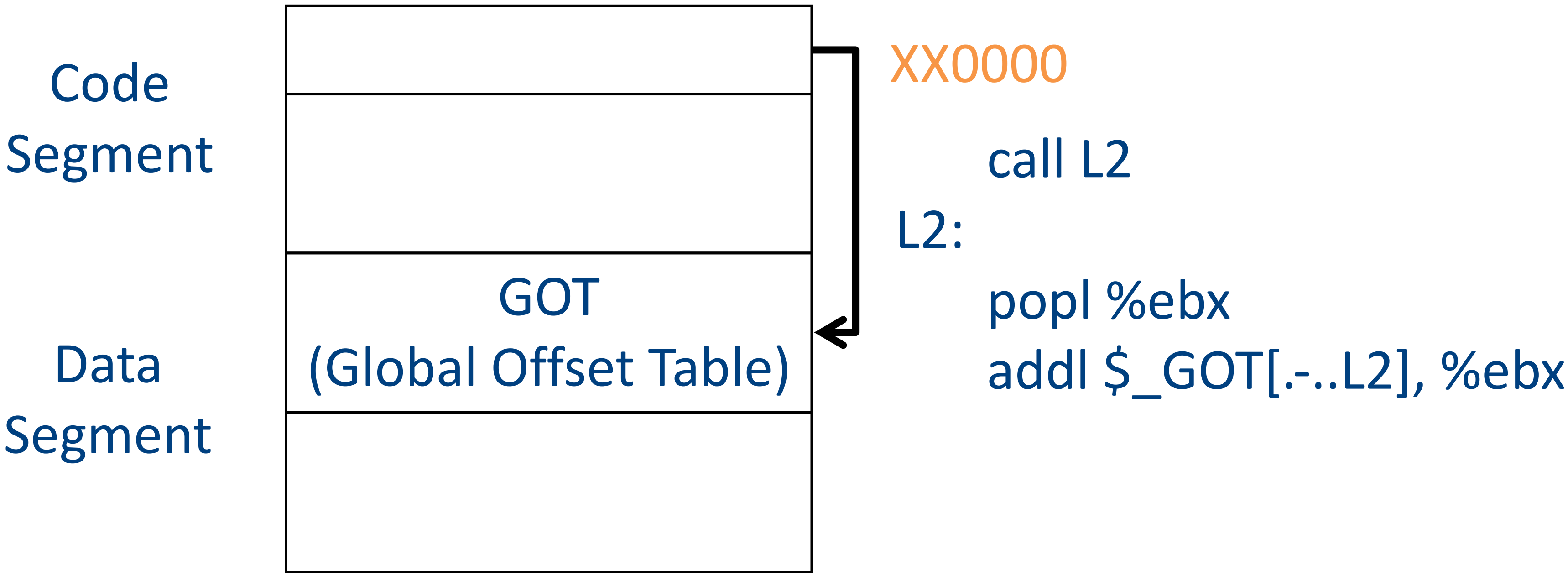
PIC: The Main Idea

- Keep the global data in a table
- Refer to all data relative to the designated register

- Efficiency: use a register to point to the beginning of the table
    - Troublesome in CISC machines

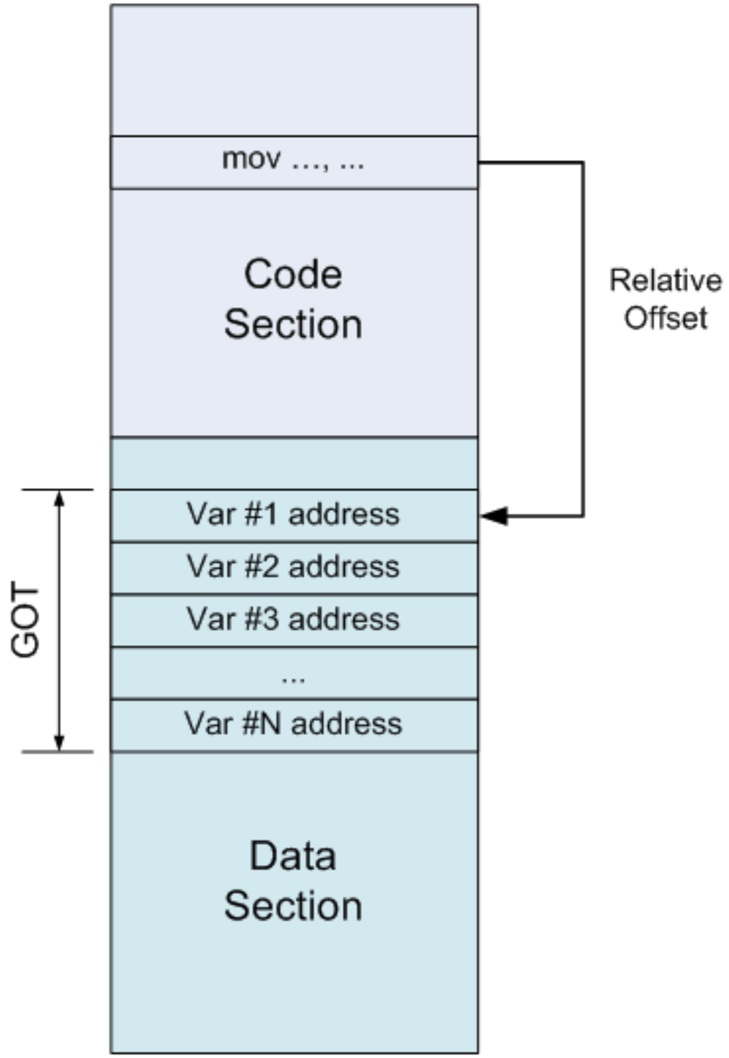
ELF-Position Independent Code

- Executable and Linkable code Format
  - Introduced in Unix System V
- Observation
  - Executable consists of code followed by data
  - The offset of the data from the beginning of the code is known at compile-time

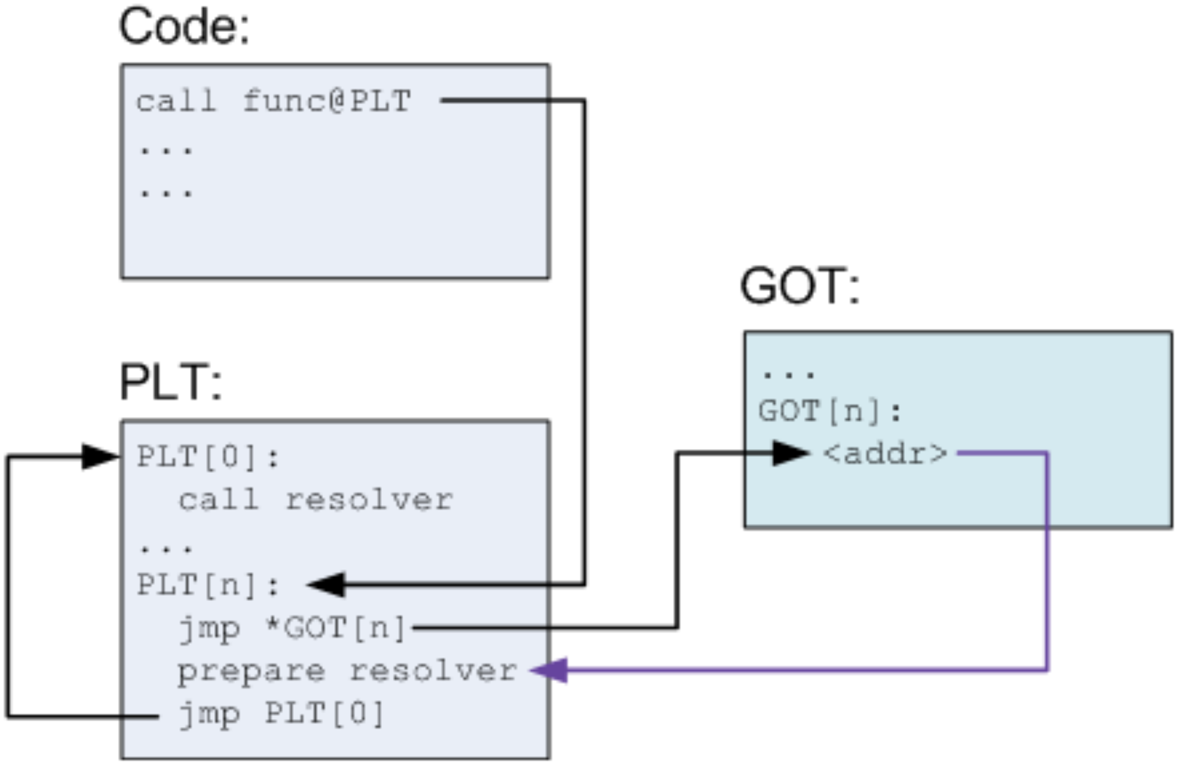


```
      call L2
L2:
      popl %ebx
      addl $_GOT[.-..L2], %ebx
```

ELF: Accessing global data



ELF: Calling Procedures
(before 1st call)



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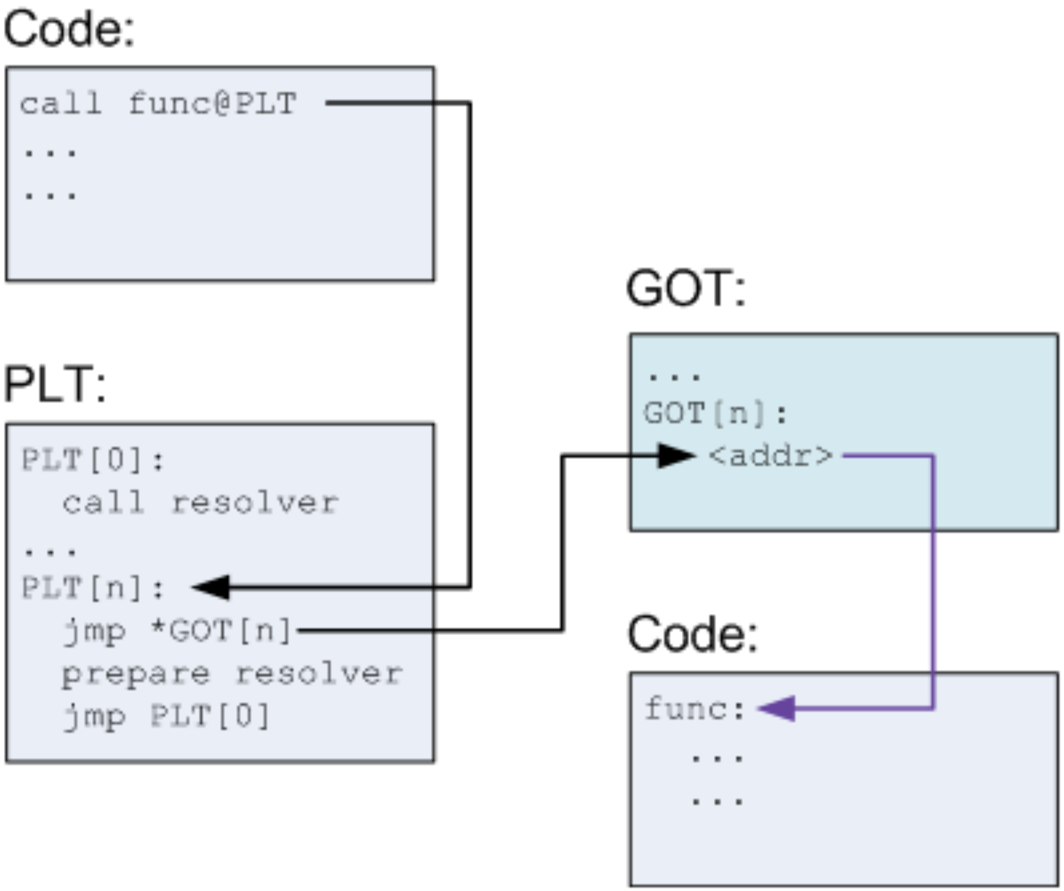


PIC benefits and costs

- Enable loading w/o relocation
- Share memory locations among processes

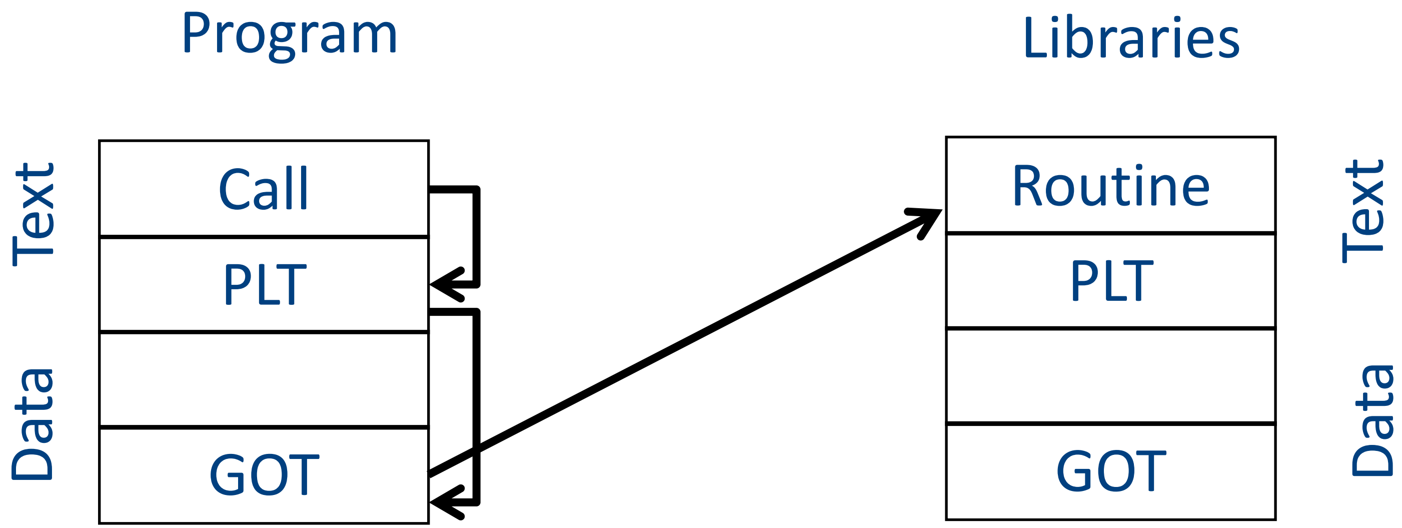
- Data segment may need to be reloaded
- GOT can be large
- More runtime overhead
- More space overhead

Shared Libraries

- Heavily used libraries
- Significant code space
  - 5-10 Mega for print
  - Significant disk space
  - Significant memory space
- Can be saved by sharing the same code
- Enforce consistency
- But introduces some overhead

- Can be implemented either with static or dynamic loading

Content of ELF file



Consistency

- How to guarantee that the code/library used the “right” library version

Loading Dynamically Linked Programs

- Start the dynamic linker
- Find the libraries
- Initialization
    - Resolve symbols
    - GOT
        - Typically small
    - Library specific initialization
- Lazy procedure linkage

Microsoft Dynamic Libraries (DLL)

- Similar to ELF
- Somewhat simpler
- Require compiler support to address dynamic libraries
- Programs and DLL are Portable Executable (PE)
- Each application has it own address
- Supports lazy bindings

Dynamic Linking Approaches

- Unix/ELF uses a single name space and MS/PE uses several name spaces
- ELF executable lists the names of symbols and libraries it needs
- PE file lists the libraries to import from other libraries
- ELF is more flexible
- PE is more efficient

Costs of dynamic loading

- Load time relocation of libraries
- Load time resolution of libraries and executable
- Overhead from PIC prolog
- Overhead from indirect addressing
- Reserved registers

Summary

- Code generation yields code which is still far from executable
    - Delegate to existing assembler
- Assembler translates symbolic instructions into binary and creates relocation bits
- Linker creates executable from several files produced by the assembly
- Loader creates an image from executable