Postcompilation

Previously…
Review – The Heap

Heap Memory

- Using the heap
- OS interface

Garbage collection

- Reference Counting
- Mark and Sweep

<u>**You Should Know**</u>

- How to program with heap memory
- The basic concepts of the two garbage collection schemes

Machine Codegen


COMPILER
LAND
Postcompilation Pit-stop
Codegen
Optimization
Architecture
Intermediate Representation
Semantic Analysis
Syntactic Definition
Parsing
Syntax-Dir Translation
Regular Languages
Lexical Analysis
8

Today's Lecture

Postcompilation

Compiler Toolchains

- Overview

Component Definitions

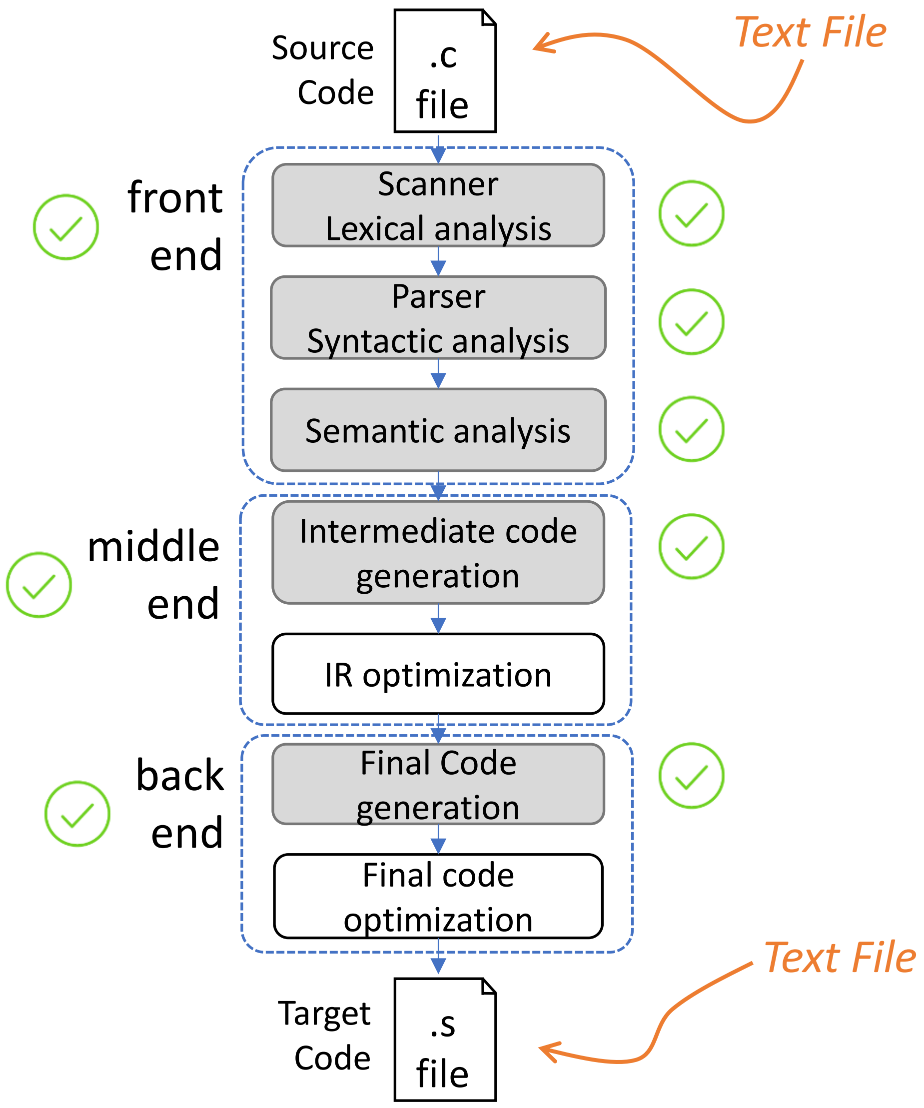
- Detour - History
- What GCC Does

Component Walkthrough

- Assembler
- Linker
- Loader

Compiler Construction: Status

Progress Pics



Implemented all modules of a non-optimizing compiler

- Front end, middle end, and back end are all complete

One detail remains

- What use is an assembly text file?

OS Perspective: Still Just Text

Compiler Toolchains - Overview

From text file to text file

- Source code and assembly code equally useless to processor

Pretty unlike that runtime understands a text format

- Nearly always a better binary representation
- Some work left after the compiler has finished

From text file to text file:
OS sees nothing accomplished

OS Perspective: Still Just Text

From text file to text file

- Source code and assembly code equally useless to processor

Pretty unlike that runtime understands a text format

- Nearly always a better binary representation
- Some work left after the compiler has finished

"Shouldn't the compiler target that?"

Compiler doesn't (need to) output object code / executables

“But when I run gcc I get a binary”

- You, maybe

Then perhaps gcc is more than a compiler!

Did I just blow your mind?

Probably not, because it’s just a matter of definitions

Compiler vs Compiler Toolchain

(A pedantic distinction)

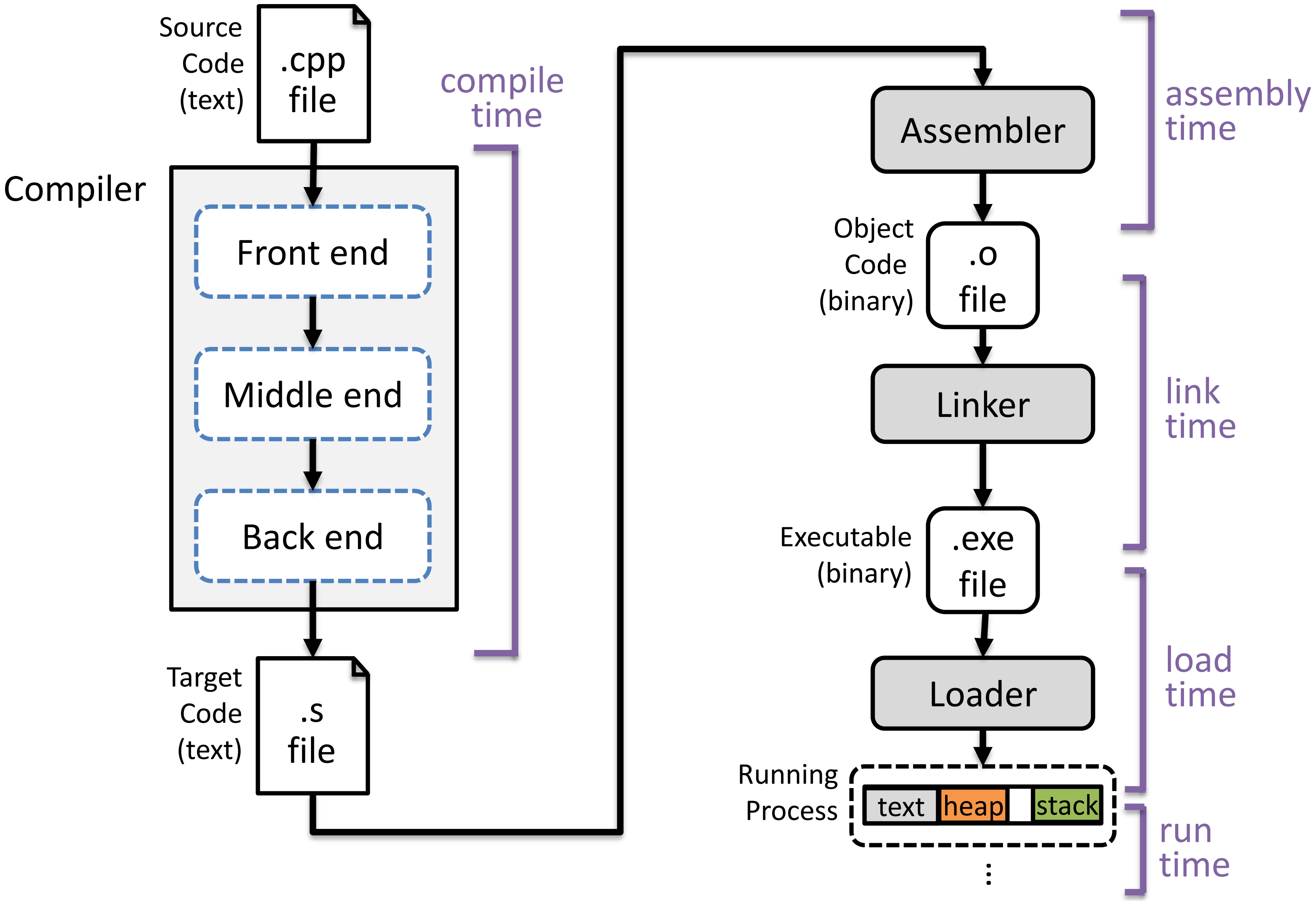
Program lifecycle components often collectively referred to as “compiler” (*vs.* compiler toolchain)*

- These components *can* be invoked separately

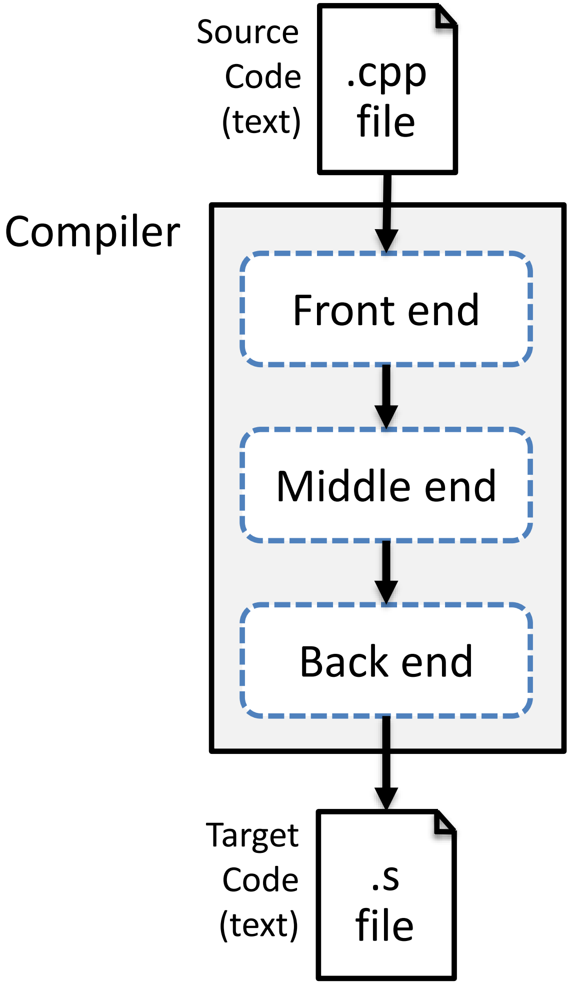
[*]: Unfortunately (in my opinion) this convention kinda erases the term for the high-level text code to low-level text code component

The Compiler Toolchain

Postcompilation - Component Walkthrough

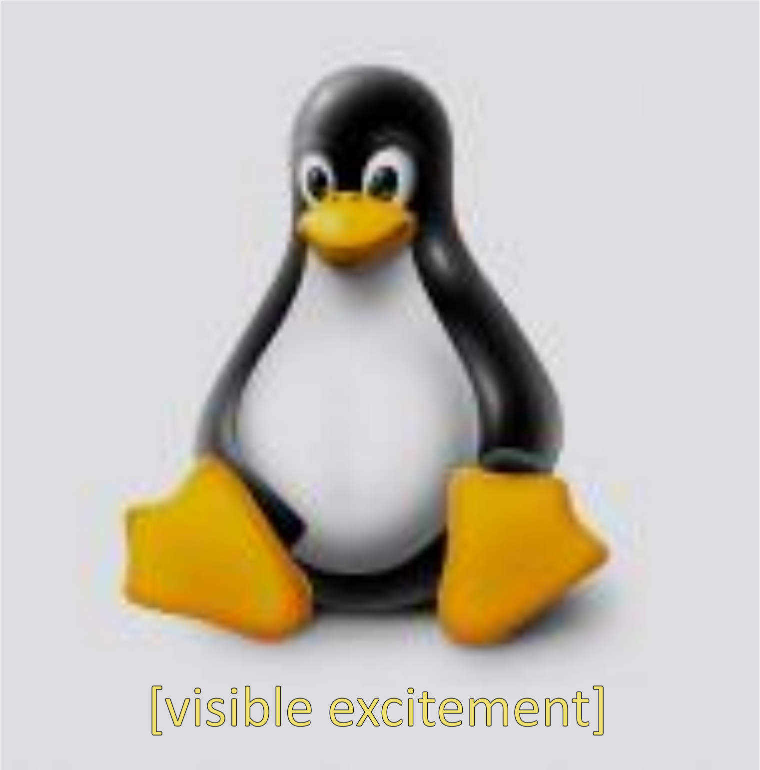


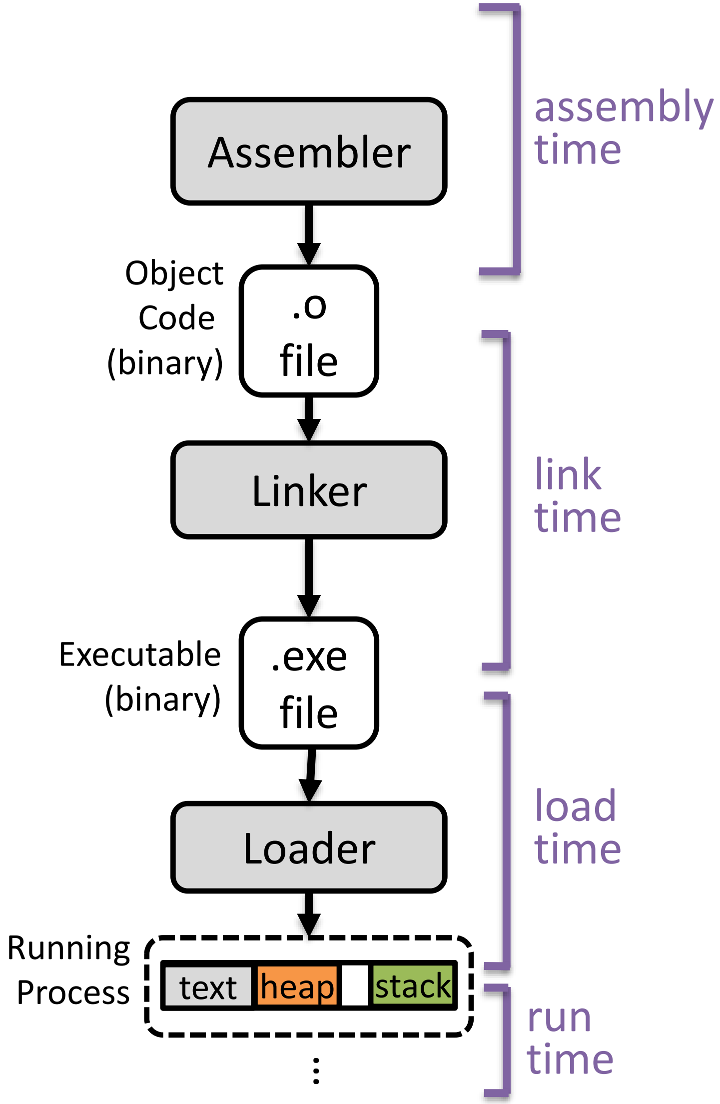
The Compiler Toolchain
Postcompilation - Component Walkthrough



The Compiler Toolchain

Postcompilation - Component Walkthrough





Today's Lecture
Postcompilation

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- Detour - History
- What GCC Does

Component Walkthrough
- Assembler
- Linker
- Loader

Defining Toolchain Components

Postcompilation - Component Walkthrough

DEFINITIONS

(They're a little bit fuzzy)

Historical Factors

Detour: Component Terminology

- Compiler toolchain largely evolved from need to handle more complex programming tasks
  - Definitions have likewise evolved, with somewhat uneven consensus

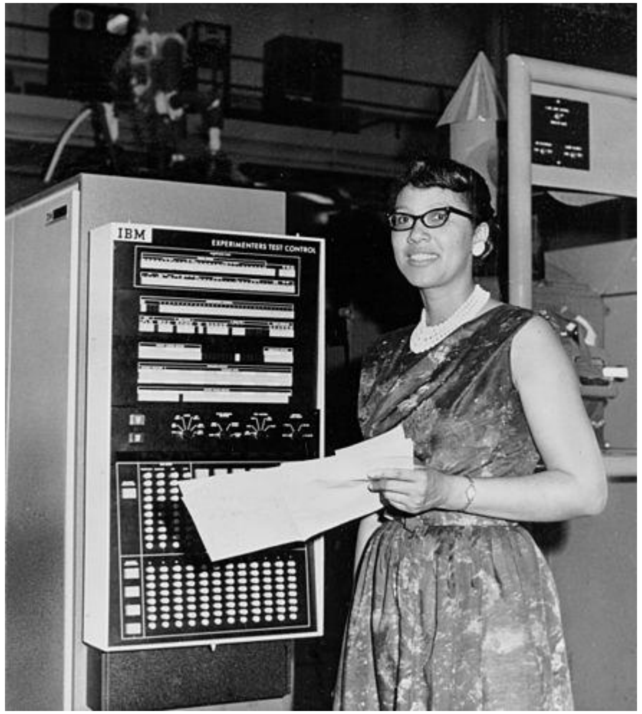
Genesis of "Computer"

Detour: Component Terminology

From 1613-1945:

- "Computer" exclusively meant "a person who carries out computations"

Original programming consists of inputting numeric machine codes



Melba Roy Mouton: Early "human computer"

Genesis of "Assembler"

Detour: Component Terminology

1949: EDSAC features first code akin to modern notion of assembler

1953: Term "assembler" popularized for a program that concretized symbolic programs

Maurice Wilkes: developed assembler for EDSAC

Nathanial Rochester: Published assembler design

Genesis of "Linker"

Detour: Component Terminology

DETOUR

1952: A-0 system features first code akin to the modern notion of a linker (confusingly called a compiler at the time)

Allowed multiple programs to be combined together before being run

Grace Hopper: developed A-0

Genesis of "Compiler"

DETOUR

Detour: Component Terminology

1951: Publication of a translator from a high-level language to low-level code, considered the first compiler

(Also specifies the compiler in new high-level language)

Corrado Böhm: published first compiler in his PhD thesis

Genesis of “Loader”

Detour: Component Terminology

DETOUR

1947: ENIAC introduces the notion of relocating code to accommodate pre-defined subroutines, a feature somewhat akin to loaders (though pre-OS)

John Mauchley: Wrote about ENIAC procedures to relocate code in memory so that debugged subprograms could be loaded

Enough History for Now

Detour: Component Terminology

Practical upshot: terms have changed somewhat

Program Lifecycle for Our Purpose

Postcompilation - Component Walkthrough

- Compile high-level source code text to low-level assembly code text — **Compiler** cc
- Assemble assembly code into object code binary modules — **Assembler** as
- Link object code into a single executable — **Linker** ld
- Load program into memory and run — **Loader** (launch program)

These modules can be invoked separately!

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The gcc “subprograms”

Fun home experiment:

- Create empty.c

```
int main(){}
```

- Run gcc in verbose mode on empty.c

```
cycle1: gcc -v empty.c
```

```
a807d786@cycle1:~/libc_link$ gcc -v empty.c
Target: x86_64-linux-gnu
[…]
Thread model: posix
gcc version 7.5.0 (Ubuntu 7.5.0-3ubuntu1~18.04)
COLLECT_GCC_OPTIONS='-v' '-mtune=generic' '-march=x86-64'
 /usr/lib/gcc/x86_64-linux-gnu/7/cc1 -quiet -v -imultiarch x86_64-linux-gnu empty.c -quiet -dumpbase empty.c -mtune=generic -
march=x86-64 -auxbase empty -version -fstack-protector-strong -Wformat -Wformat-security -o /tmp/ccs6BRmG.s
[…]
GNU C11 (Ubuntu 7.5.0-3ubuntu1~18.04) version 7.5.0 (x86_64-linux-gnu)
	compiled by GNU C version 7.5.0, GMP version 6.1.2, MPFR version 4.0.1, MPC version 1.1.0, isl version isl-0.19-GMP

GGC heuristics: --param ggc-min-expand=100 --param ggc-min-heapsize=131072
Compiler executable checksum: b62ed4a2880cd4159476ea8293b72fa8
COLLECT_GCC_OPTIONS='-v' '-mtune=generic' '-march=x86-64'
 as -v --64 -o /tmp/cc4FfCb1.o /tmp/ccs6BRmG.s
[…]
COLLECT_GCC_OPTIONS='-v' '-mtune=generic' '-march=x86-64'
 /usr/lib/gcc/x86_64-linux-gnu/7/collect2 -plugin /usr/lib/gcc/x86_64-linux-gnu/7/liblto_plugin.so -plugin-opt=/usr/lib/gcc/x86_64-
linux-gnu/7/lto-wrapper -plugin-opt=-fresolution=/tmp/ccAxjj1l.res -plugin-opt=-pass-through=-lgcc -plugin-opt=-pass-through=-lgcc_s -
plugin-opt=-pass-through=-lc -plugin-opt=-pass-through=-lgcc -plugin-opt=-pass-through=-lgcc_s --build-id --eh-frame-hdr -m elf_x86_64
--hash-style=gnu --as-needed -dynamic-linker /lib64/ld-linux-x86-64.so.2 -pie -z now -z relro /usr/lib/gcc/x86_64-linux-
gnu/7/../../../x86_64-linux-gnu/Scrt1.o /usr/lib/gcc/x86_64-linux-gnu/7/../../../x86_64-linux-gnu/crti.o /usr/lib/gcc/x86_64-linux-
gnu/7/crtbeginS.o -L/usr/lib/gcc/x86_64-linux-gnu/7 -L/usr/lib/gcc/x86_64-linux-gnu/7/../../../x86_64-linux-gnu -L/usr/lib/gcc/x86_64-
linux-gnu/7/../../../../lib -L/lib/x86_64-linux-gnu -L/lib/../lib -L/usr/lib/x86_64-linux-gnu -L/usr/lib/../lib -L/usr/lib/x86_64-linux-gnu -
L/usr/lib/gcc/x86_64-linux-gnu/7/../../.. /tmp/cc4FfCb1.o -lgcc --push-state --as-needed -lgcc_s --pop-state -lc -lgcc --push-state --as-
needed -lgcc_s --pop-state /usr/lib/gcc/x86_64-linux-gnu/7/crtendS.o /usr/lib/gcc/x86_64-linux-gnu/7/../../../x86_64-linux-gnu/crtn.o
COLLECT_GCC_OPTIONS='-v' '-mtune=generic' '-march=x86-64'
```

The compiler proper

Source code (input)

Assembly code

The assembler

Object code

The linker

Runtime components

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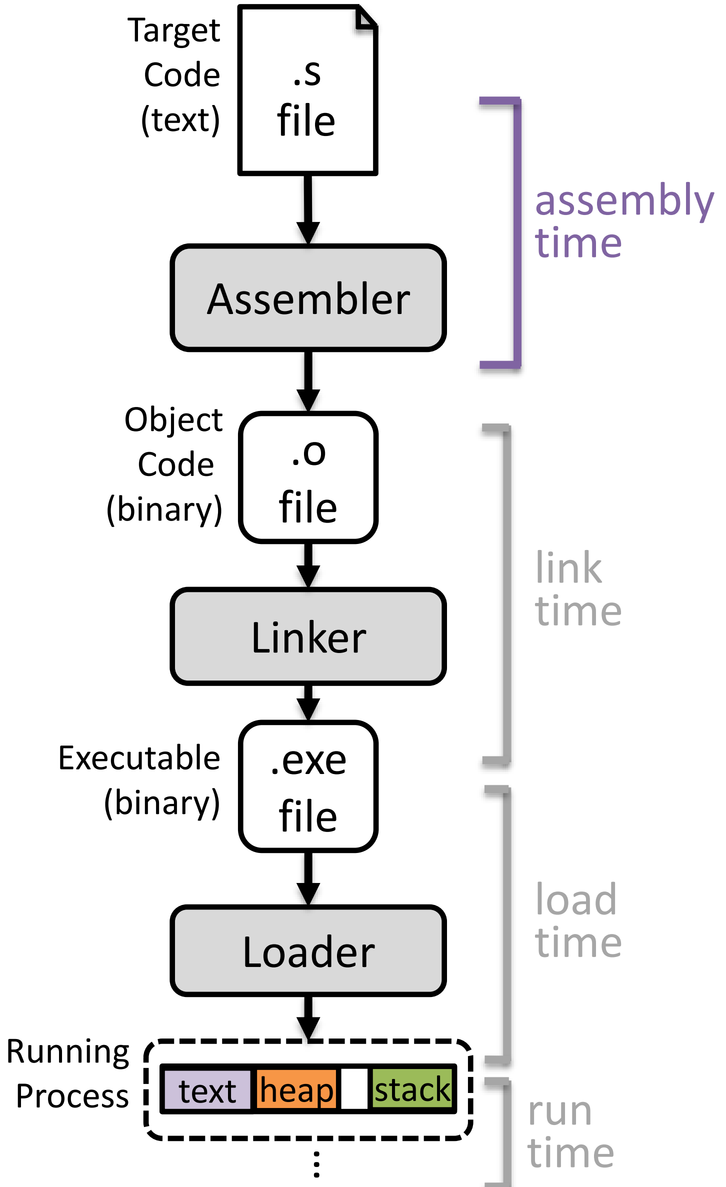
The Assembler
Module Role and Operation

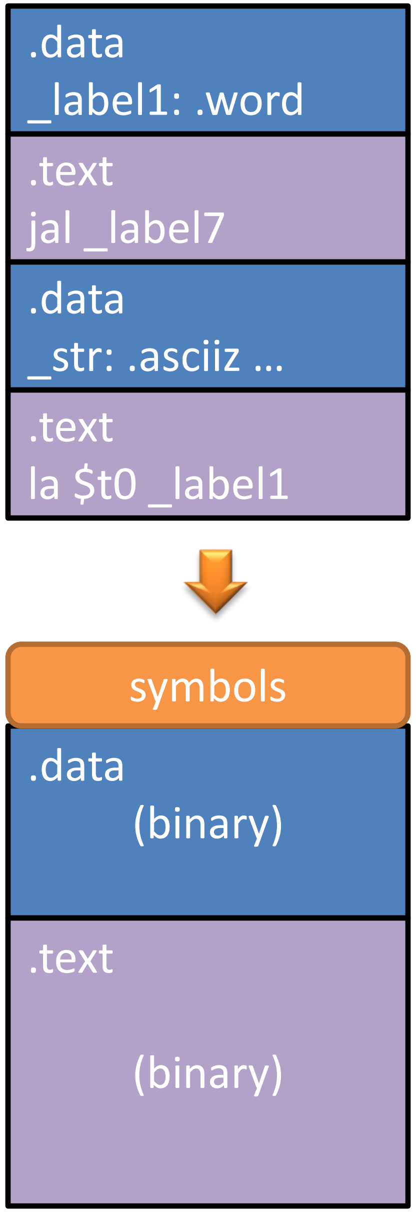
- Modern use:
  - Translates labels and instruction mnemonics to binary equivalent
- Output may still contain placeholders for some code and data



The Assembler: Responsibilities

Module Role and Operation

- Collect symbolic definitions (e.g. labels) into “low-level” symbol table
- Put code and data into segments
- Replace uses of labels with placeholder addresses (where available)



The Assembler

Module Role and Operation

src code

```
.data
gbl: .quad 12
.globl _start
.text
_start: jmp _start

```

```
as -o out.o file.s
objdump -Dwrt out.o
```

object code

```

code.o:     file format elf64-x86-64

SYMBOL TABLE:
0000000000000000 l    d  .text  0000000000000000 .text
0000000000000000 l    d  .data  0000000000000000 .data
0000000000000000 l    d  .bss   0000000000000000 .bss
0000000000000000 l       .data  0000000000000000 gbl
0000000000000000 g       .text  0000000000000000 _start



Disassembly of section .text:

0000000000000000 <_start>:
   0:   eb fe                   jmp    0 <_start>

Disassembly of section .data:

0000000000000000 <gbl>:
   0:   0c 00                   or     $0x0,%al
   2:   00 00                   add    %al,(%rax)
   4:   00 00                   add    %al,(%rax)
        ...
```

The Assembler: Invocation

Module Role and Operation

```
(to get assembly): cc –S ret3.c –o /tmp/a.s
```

```
as /tmp/a.s  -o /tmp/a.o
```

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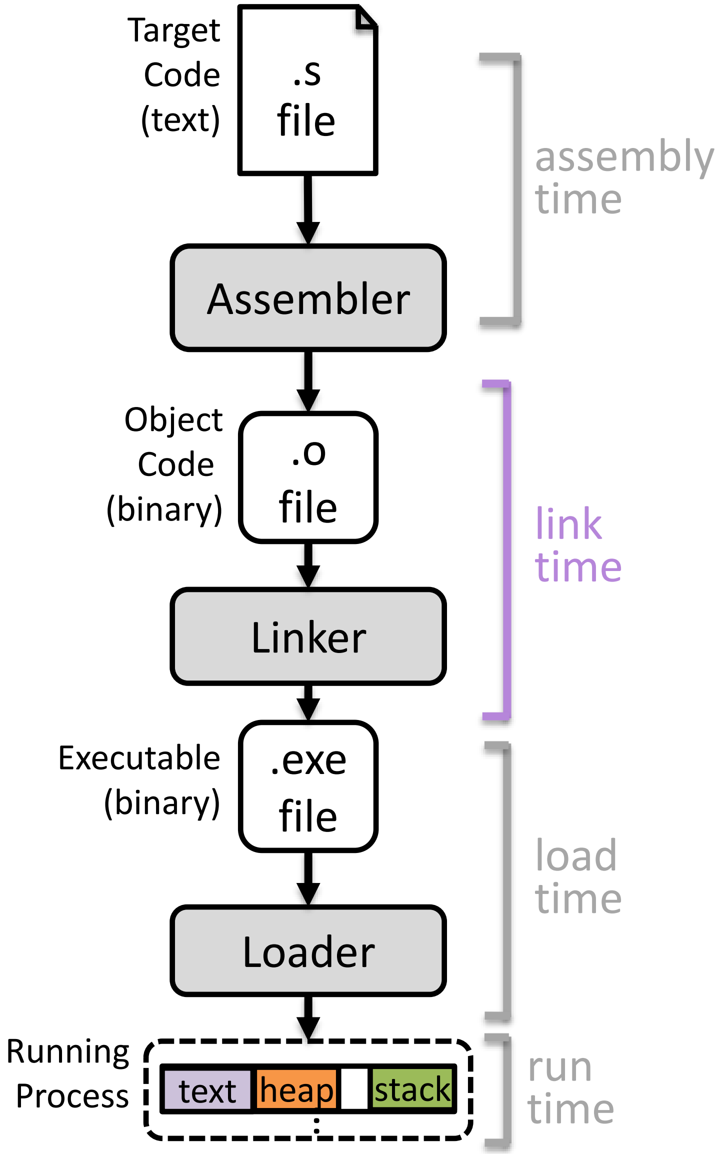
The Linker
Module Role and Operation

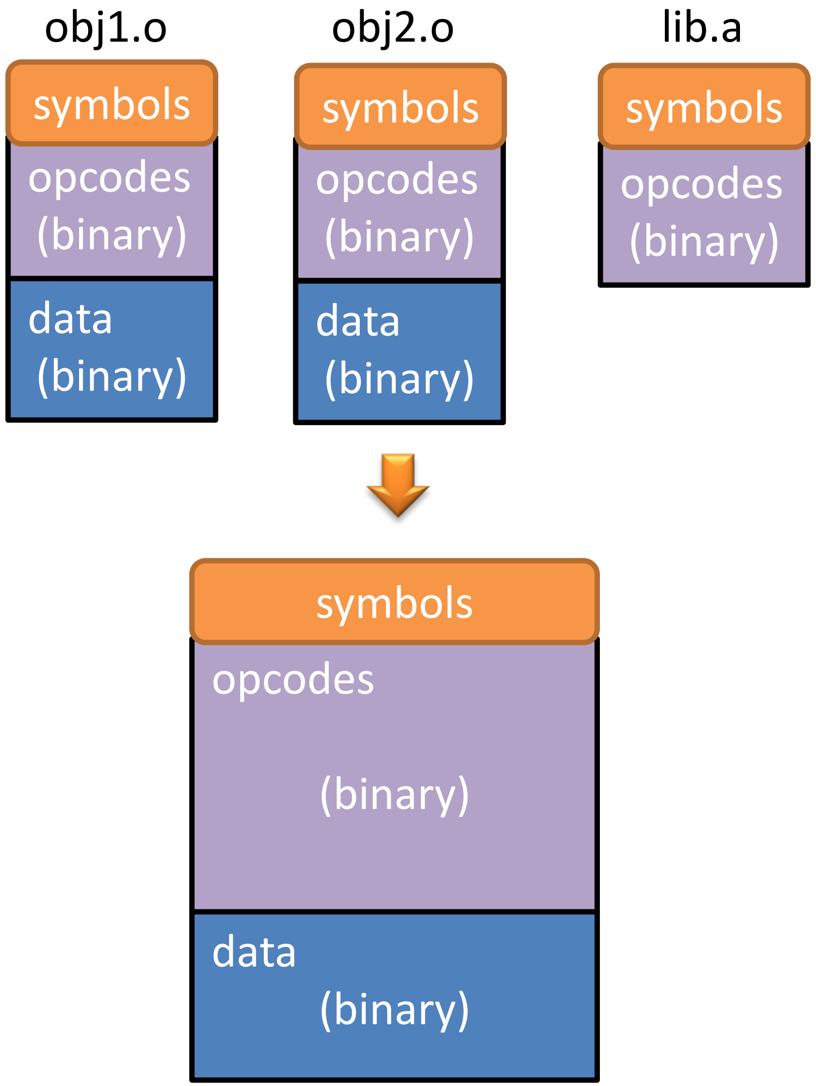
- Resolves placeholders betwixt multiple object files
- Stitches objects files (and static libraries) into a single binary



The Linker: Responsibilities

Module Role and Operation

- Calculate segment size
- Relocate segments
- Resolve symbol imports with exports where available
  - *e.g. call in obj1.o, callee in obj2.o*
- Add initialization routines
- Optimization!



The Linker

Module Role and Operation

```
ld -o prog code.o
objdump -Dwrt prog
```

Object code

```

code.o:     file format elf64-x86-64

SYMBOL TABLE:
0000000000000000 l    d  .text  0000000000000000 .text
0000000000000000 l    d  .data  0000000000000000 .data
0000000000000000 l    d  .bss   0000000000000000 .bss
0000000000000000 l       .data  0000000000000000 gbl
0000000000000000 g       .text  0000000000000000 _start



Disassembly of section .text:

0000000000000000 <_start>:
   0:   eb fe                   jmp    0 <_start>

Disassembly of section .data:

0000000000000000 <gbl>:
   0:   0c 00                   or     $0x0,%al
   2:   00 00                   add    %al,(%rax)
   4:   00 00                   add    %al,(%rax)
        ...
```

Executable code

```

code.prog:     file format elf64-x86-64

SYMBOL TABLE:
00000000004000b0 l    d  .text  0000000000000000 .text
00000000006000b2 l    d  .data  0000000000000000 .data
0000000000000000 l    df *ABS*  0000000000000000 code.o
00000000006000b2 l       .data  0000000000000000 gbl
00000000004000b0 g       .text  0000000000000000 _start
00000000006000ba g       .data  0000000000000000 __bss_start
00000000006000ba g       .data  0000000000000000 _edata
00000000006000c0 g       .data  0000000000000000 _end



Disassembly of section .text:

00000000004000b0 <_start>:
  4000b0:       eb fe                   jmp    4000b0 <_start>

Disassembly of section .data:

00000000006000b2 <gbl>:
  6000b2:       0c 00                   or     $0x0,%al
  6000b4:       00 00                   add    %al,(%rax)
  6000b6:       00 00                   add    %al,(%rax)
        ...
```

The Linker: Simple Invocation

Module Role and Operation

Project concept

The simplest use, “linking” a single object file:

```
ld prog.o -o prog.exe
```

More complex use, linking multiple object files

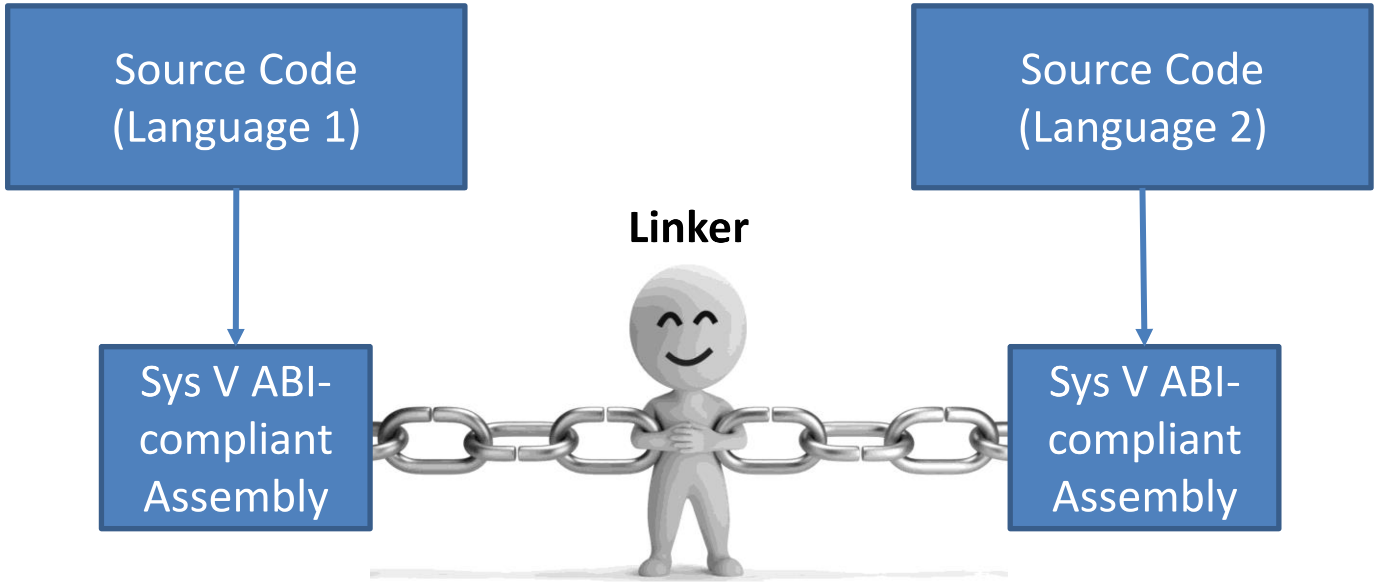
```
ld prog.o a.o b.o -o a.exe
```

Cross-language linking

Module Role and Operation

Object code is raw x64 code (containing placeholders)

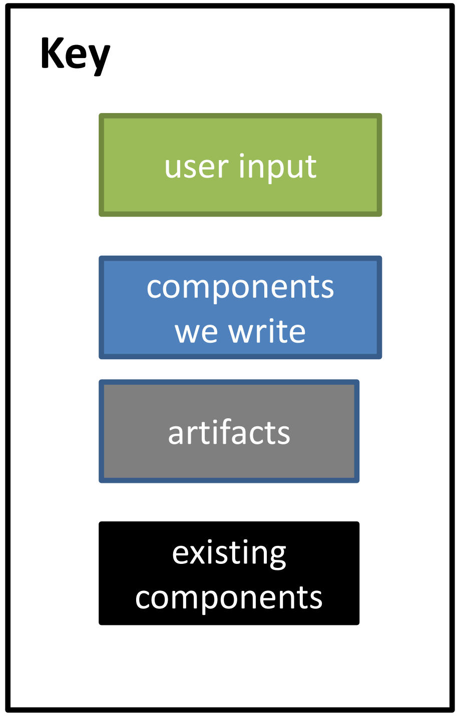
- Should obey the System V ABI
- We can link with object code from other languages!

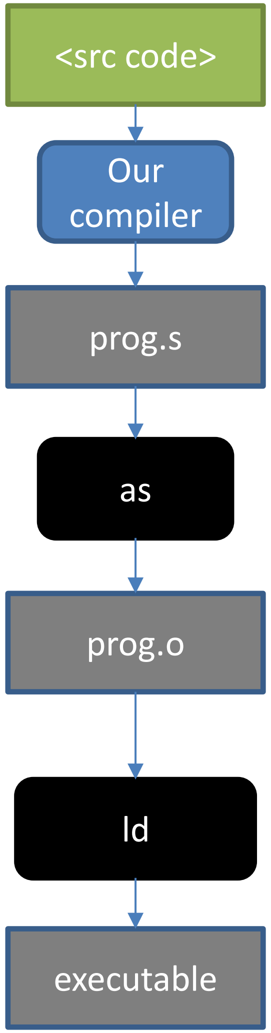


Cross-language linking

Module Role and Operation

End-to-end compiler toolchain workflow

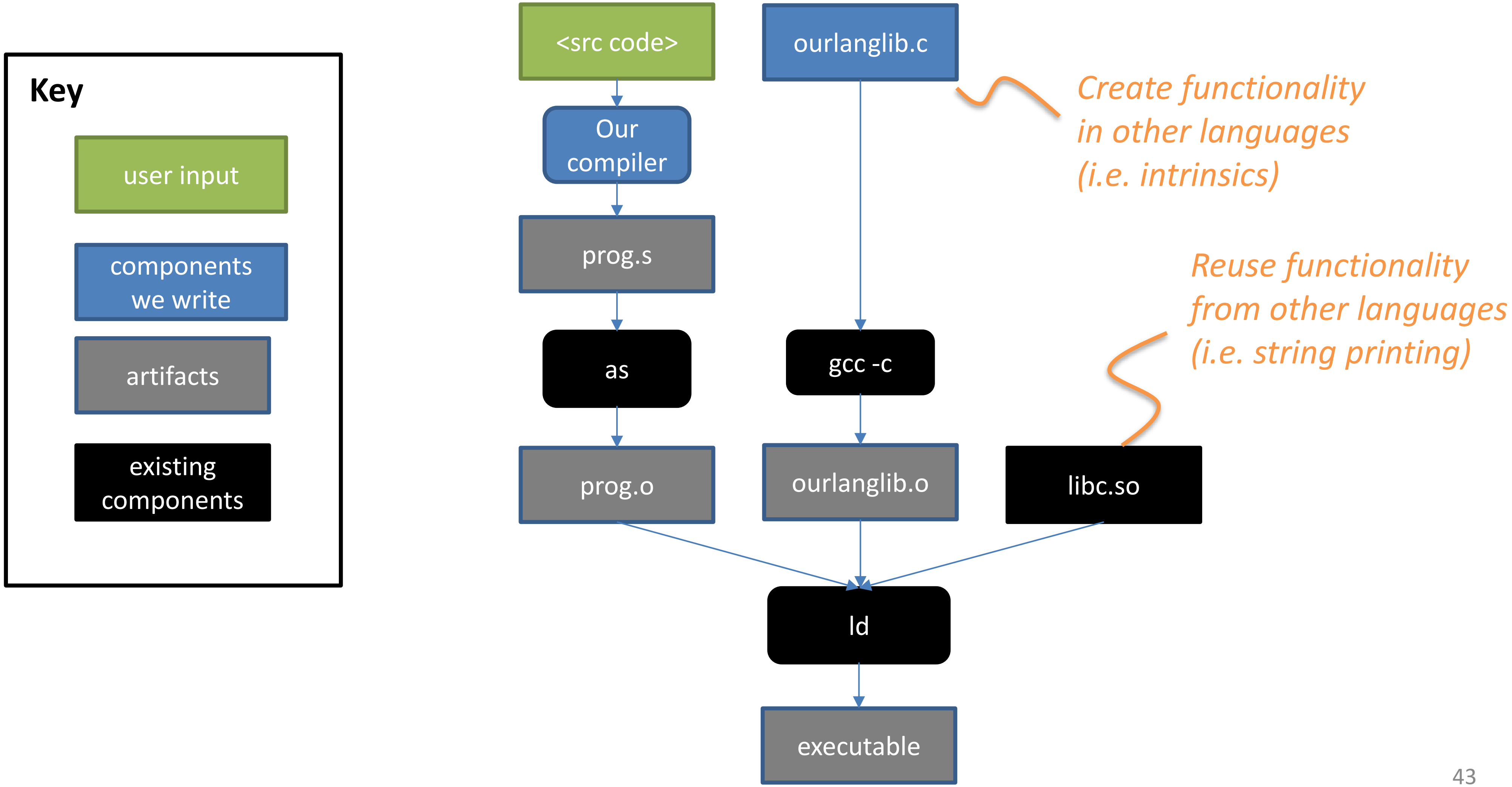




Cross-language linking

Module Role and Operation

End-to-end compiler toolchain workflow



Benefits of Cross-Linking

Module Role and Operation

Project concept

Inter-language compatibility

- Let each language's strengths shine

Functionality reuse

- Avoid coding against the OS directly

Do not reinvent this

Why use the C Runtime?

Module Role and Operation

Project concept

Src Code

```
int main(){
   output 7;
}
```

https://blog.rchapman.org/posts/Linux_System_Call_Table_for_x86_64/

%rax	System call	%rdi	%rsi	%rdx
0	sys_read	unsigned int fd	char *buf	size_t count
1	sys_write	unsigned int fd	const char *buf	size_t count

Why use the C Runtime?

Module Role and Operation

Project concept

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}
```

Asm Code

```
.globl _start
.text
_start: callq fn_main
        movq %rax, %rdi
        movq $60, %rax
        syscall
fn_main: <fn prologue>
         # output 7
         …
         syscall
         <fn epilogue>
```

%rax	System call	%rdi	%rsi	%rdx
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         movq ???????, %rsi #buffer address
         …
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%rax	System call	%rdi	%rsi	%rdx
0	sys_read	unsigned int fd	char *buf	size_t count
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Why use the C Runtime?
Module Role and Operation

Project concept

Src Code

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int main(){
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}
```

Asm Code

```
.data
buffer: .asciz “?”
.globl _start
.text
_start: callq fn_main
        movq %rax, %rdi
        movq $60, %rax
        syscall
fn_main: <fn prologue>
         # output 7
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         movq $buffer, %rsi #buffer address
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         # output 7
         movq $1, %rax #select sys_write
         movq $1, %rdi #write to stdout
         movq $buffer, %rsi #buffer address
movq $0x37, (buffer)   ~~movq $7, (buffer)~~   #write to buffer
         …
         syscall
         <fn epilogue>
```

%rax	System call	%rdi	%rsi	%rdx
0	sys_read	unsigned int fd	char *buf	size_t count
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Module Role and Operation

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         movq $1, %rax #select sys_write
         movq $1, %rdi #write to stdout
         movq $buffer, %rsi #buffer address
         movq $0x37, (buffer)#write to buffer
         movq $1, %rdx #string length
         syscall
         <fn epilogue>
```

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         movq $0x37, (buffer)#write to buffer
         movq $1, %rdx #string length
         syscall
         <fn epilogue>
```

It gets even worse!

Why use the C Runtime?

Module Role and Operation

Project concept

Src Code

```
…
int main(){
  output gbl;
}
```

Asm Code

```
fn_main: <fn prologue>
         # output gbl
         movq $1, %rax #select sys_write
         movq $1, %rdi #write to stdout
         movq $buffer, %rsi #string to print
         movq ??, (buffer) #write characters to buffer
         movq ??, %rdx #string length
         syscall
         <fn epilogue>
```

"I miss printf"

Prefill Buffer to all null bytes?

Loop over Buffer counting non-null bytes?

Repeatedly call idivq $10?

Gbl: 173

Buffer:

0x31	0x37	0x33
ASCII 1	*ASCII 7*	*ASCII 3*

Use the C Runtime

Module Role and Operation

Project concept

Src Code

```
int main(){
  output 7;
}
```

Old assembly

```
.globl _start
.data
buffer: .asciz "?"
.text
_start: callq fn_main
        movq %rax, %rdi
        movq $60, %rax
        syscall
fn_main: <fn prologue>
         # output 7
         movq $1, %rax #select sys_write
         movq $1, %rdi #write to stdout
         movq $buffer, %rsi #string to print
         movq $31, (buffer) #write to buffer
         movq $1, %rdx #string length
         syscall
         <fn epilogue>
```

New Assembly

```
.text
main: <fn prologue>
      # output 7
      movq $7, %rdi #int to print
      callq myPrintInt
      <fn epilogue>
```

myStdLib

```
#include <stdio.h>
#include <inttypes.h>
void myPrintInt(int64_t arg){
  fprintf(stdout, "%ld", arg);
}
```

Use the C Runtime

Module Role and Operation

Project concept

Src Code

```
int main(){
  output 7;
}
```

prog.o

User code
(calls myPrintInt)

mystdlib.o

Shim code
(calls fprintf)

C runtime

fprintf definition
_start label
and so much more!

New Assembly

```
.text
main: <fn prologue>
      # output 7
      movq $7, %rdi #int to print
      callq myPrintInt
      <fn epilogue>
```

myStdLib

```
#include <stdio.h>
#include <inttypes.h>
void myPrintInt(int64_t arg){
  fprintf(stdout, “%ld”, arg);
}
```

Basing our runtime on C's

Module Role and Operation


Project concept

```
SYSPATH=/usr/lib/x86_64-linux-gnu
ld \
  -dynamic-linker /lib64/ld-linux-x86-64.so.2 \
  $SYSPATH/crt1.o \
  $SYSPATH/crti.o \
  -lc \
  prog.o \
  $SYSPATH/crtn.o \
  -o prog.exe
```

enable dynamic linking (-dynamic-linker /lib64/ld-linux-x86-64.so.2)

entrypoint code (crt1.o)

```
_start: exit(main)
```

init runtime data structures (crti.o)

link the libc library (-lc)

release runtime data structures (crtn.o)

Today's Lecture

Postcompilation

Compiler Toolchains

- Overview

Component Definitions

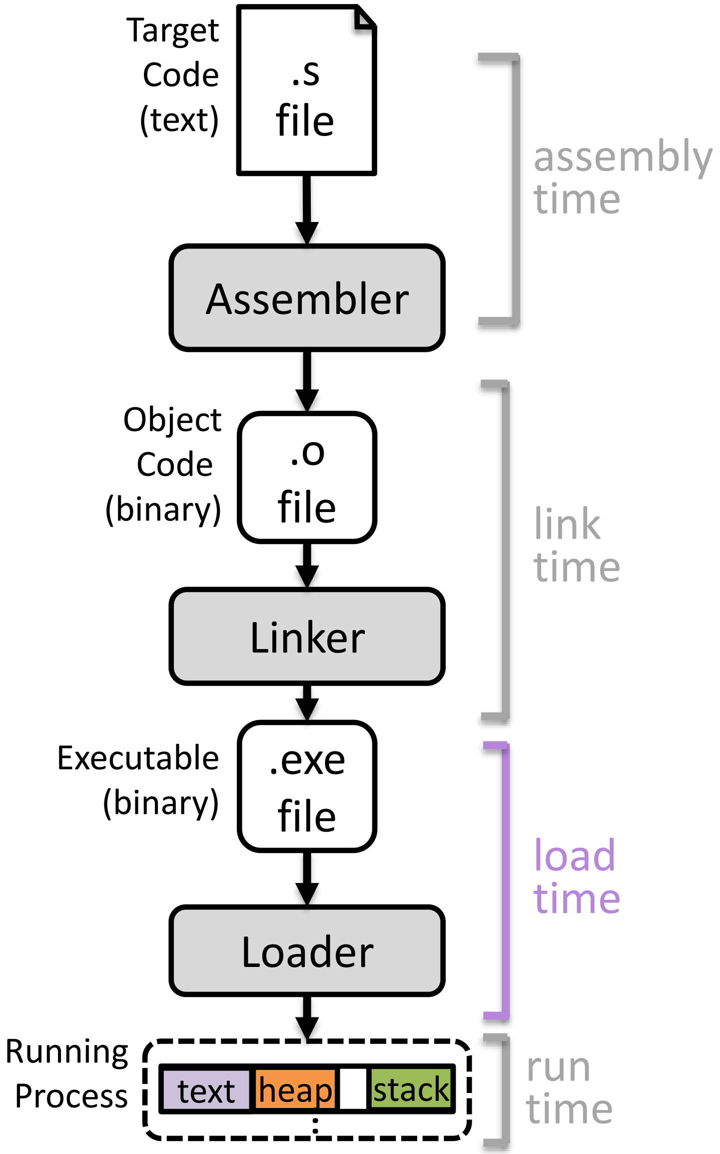
- Detour - History
- What GCC Does

Component Walkthrough

- Assembler
- Linker
- Loader

The Loader
Module Role and Operation

- Move code from secondary storage (disk) into primary storage (RAM)
- Resolves placeholders for dynamically-linked libraries (e.g. .so files)
- Kick off the program



The Loader

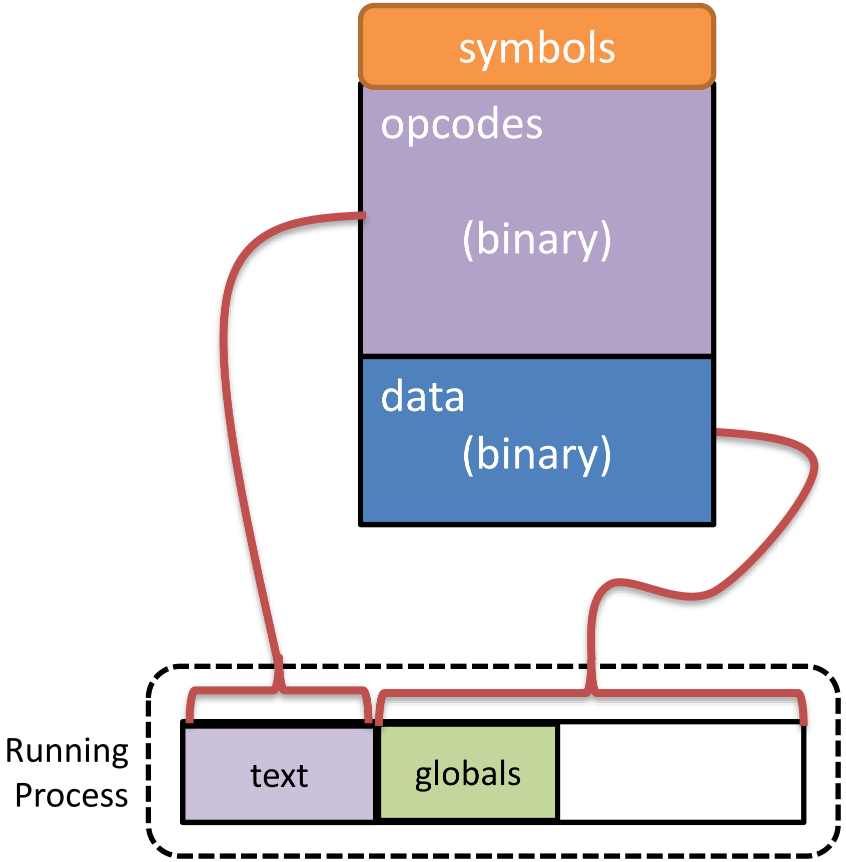
Module Role and Operation

Historically:

- Map program code into free memory
- May need to relocate symbols again

Modern Loaders:

- Simpler, as virtual memory handles physical address mapping
- Resolves dynamically-loaded libraries (.so, .dll)
- Part of the Operating System



That's all the Components!

Postcompilation: Underview

This basic process completes the "lifecycle" from source code to process

- From source to assembly
- From assembly to object code
- From object code to executable
- From executable to running process

Lecture Summary

Postcompilation: Underview

This Lecture

- Conceptual workflow from source text to process
- Tooling to perform this process
- Using cross-language linking to avoid re-implementation

Project concept

Next up: Optimization!

- Improving on the naïve code generation we've performed
  - Better machine code
  - Better intermediate code