Generating Code and Running Programs

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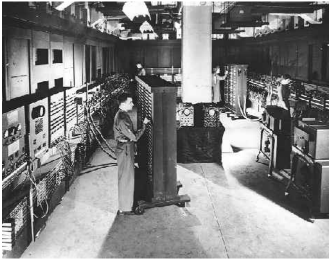
Fall 2011



Part I

The Compilation Process

A Long K's Journey into Byte†

Compiler front end {
- Source code
- ↓ Parser/Semantic Analysis
- AST

Compiler back end {
- ↓ Intermediate code generation
- IR
- ↓ Optimization
- Assembly Code

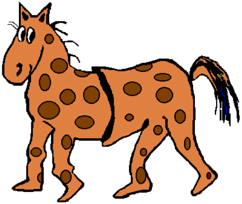
Assembler {
- ↓ Assemble
- Relocatable Object Code

Linker {
- ↓ Link
- Executable

Loader {
- ↓ Relocate
- In-memory image

†Apologies to O'Neill

Compiler Frontends and Backends



The front end focuses on *analysis*:

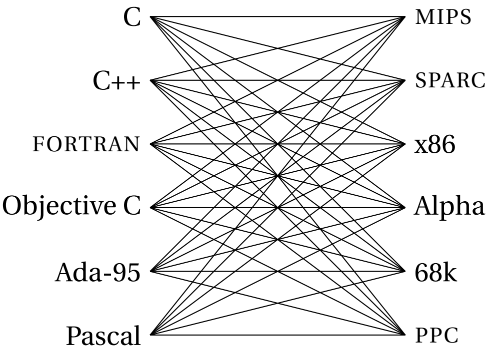
- Lexical analysis
- Parsing
- Static semantic checking
- AST generation

The back end focuses on *synthesis*:

- Translation of the AST into intermediate code
- Optimization
- Generation of assembly code

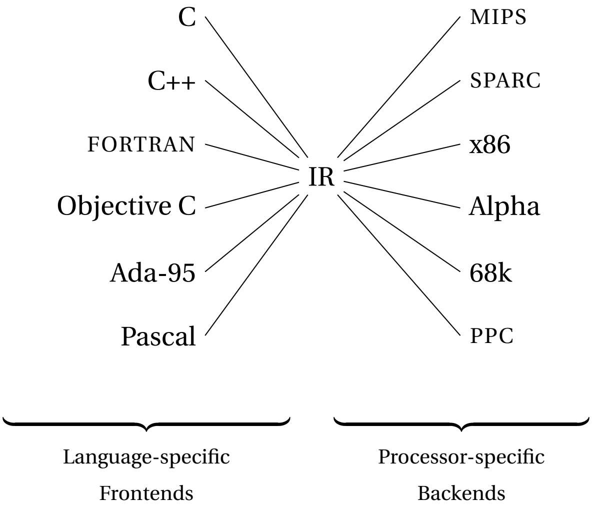
Portable Compilers

Building a compiler a large undertaking; most try to leverage it by making it portable.



Portable Compilers

Building a compiler a large undertaking; most try to leverage it by making it portable.



Part II

Intermediate Representations/Formats

Stack-Based IR: Java Bytecode

```
int gcd(int a, int b) {
  while (a != b) {
    if (a > b)
      a -= b;
    else
      b -= a;
  }
  return a;
}
```

```
# javap -c Gcd

Method int gcd(int, int)
   0 goto 19

   3 iload_1        // Push a
   4 iload_2        // Push b
   5 if_icmple 15   // if a <= b goto 15

   8 iload_1        // Push a
   9 iload_2        // Push b
  10 isub           // a - b
  11 istore_1       // Store new a
  12 goto 19

  15 iload_2        // Push b
  16 iload_1        // Push a
  17 isub           // b - a
  18 istore_2       // Store new b

  19 iload_1        // Push a
  20 iload_2        // Push b
  21 if_icmpne 3    // if a != b goto 3

  24 iload_1        // Push a
  25 ireturn        // Return a
```

Stack-Based IRs

Advantages:

- Trivial translation of expressions
- Trivial interpreters
- No problems with exhausting registers
- Often compact

Disadvantages:

- Semantic gap between stack operations and modern register machines
- Hard to see what communicates with what
- Difficult representation for optimization

Register-Based IR: Mach SUIF

```
int gcd(int a, int b) {
  while (a != b) {
    if (a > b)
      a -= b;
    else
      b -= a;
  }
  return a;
}
```

```
gcd:
gcd._gcdTmp0:
  sne    $vr1.s32 <- gcd.a,gcd.b
  seq    $vr0.s32 <- $vr1.s32,0
  btrue  $vr0.s32,gcd._gcdTmp1    // if!(a != b) goto Tmp1

  sl     $vr3.s32 <- gcd.b,gcd.a
  seq    $vr2.s32 <- $vr3.s32,0
  btrue  $vr2.s32,gcd._gcdTmp4    // if!(a < b) goto Tmp4

  mrk    2, 4     // Line number 4
  sub    $vr4.s32 <- gcd.a,gcd.b
  mov    gcd._gcdTmp2 <- $vr4.s32
  mov    gcd.a <- gcd._gcdTmp2    // a = a - b
  jmp    gcd._gcdTmp5
gcd._gcdTmp4:
  mrk    2, 6
  sub    $vr5.s32 <- gcd.b,gcd.a
  mov    gcd._gcdTmp3 <- $vr5.s32
  mov    gcd.b <- gcd._gcdTmp3    // b = b - a
gcd._gcdTmp5:
  jmp    gcd._gcdTmp0

gcd._gcdTmp1:
  mrk    2, 8
  ret    gcd.a    // Return a
```

Register-Based IRs

Most common type of IR

Advantages:

- Better representation for register machines
- Dataflow is usually clear

Disadvantages:

- Slightly harder to synthesize from code
- Less compact
- More complicated to interpret

Part III

Introduction to Optimization

Optimization In Action

```c
int gcd(int a, int b) {
  while (a != b) {
    if (a < b) b -= a;
    else a -= b;
  }
  return a;
}
```

GCC on SPARC

```
gcd:   save %sp, -112, %sp
       st   %i0, [%fp+68]
       st   %i1, [%fp+72]
.LL2:  ld   [%fp+68], %i1
       ld   [%fp+72], %i0
       cmp  %i1, %i0
       bne  .LL4
       nop
       b    .LL3
       nop
.LL4:  ld   [%fp+68], %i1
       ld   [%fp+72], %i0
       cmp  %i1, %i0
       bge  .LL5
       nop
       ld   [%fp+72], %i0
       ld   [%fp+68], %i1
       sub  %i0, %i1, %i0
       st   %i0, [%fp+72]
       b    .LL2
       nop
.LL5:  ld   [%fp+68], %i0
       ld   [%fp+72], %i1
       sub  %i0, %i1, %i0
       st   %i0, [%fp+68]
       b    .LL2
       nop
.LL3:  ld   [%fp+68], %i0
       ret
       restore
```

GCC -O7 on SPARC

```
gcd:   cmp    %o0, %o1
       be     .LL8
       nop
.LL9:  bge,a  .LL2
       sub    %o0, %o1, %o0
       sub    %o1, %o0, %o1
.LL2:  cmp    %o0, %o1
       bne    .LL9
       nop
.LL8:  retl
       nop
```

Typical Optimizations

- Folding constant expressions
  1+3 → 4
- Removing dead code
  if (0) { . . . } → nothing
- Moving variables from memory to registers

```
ld   [%fp+68], %i1
sub  %i0, %i1, %i0 → sub   %o1, %o0, %o1
st   %i0, [%fp+72]
```

- Removing unnecessary data movement
- Filling branch delay slots (Pipelined RISC processors)
- Common subexpression elimination

Machine-Dependent vs. -Independent Optimization

No matter what the machine is, folding constants and eliminating dead code is always a good idea.

```
a = c + 5 + 3;
if (0 + 3) {
  b = c + 8;
}
```

→

```
b = a = c + 8;
```

However, many optimizations are processor-specific:

- Register allocation depends on how many registers the machine has
- Not all processors have branch delay slots to fill
- Each processor's pipeline is a little different

Basic Blocks

```
int gcd(int a, int b) {
  while (a != b) {
    if (a < b) b -= a;
    else a -= b;
  }
  return a;
}
```

lower →

```
A: sne t, a, b
   bz  E, t
   slt t, a, b
   bnz B, t
   sub b, b, a
   jmp C
B: sub a, a, b
C: jmp A
E: ret a
```

split →

```
A: sne t, a, b
   bz  E, t

   slt t, a, b
   bnz B, t

   sub b, b, a
   jmp C

B: sub a, a, b

C: jmp A

E: ret a
```

The statements in a basic block all run if the first one does.

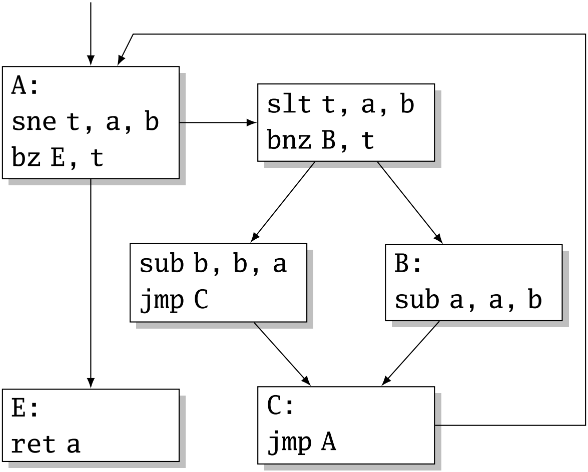
Starts with a statement following a conditional branch or is a branch target.

Usually ends with a control-transfer statement.

Control-Flow Graphs

A CFG illustrates the flow of control among basic blocks.

```
A:
sne t, a, b
bz  E, t

slt t, a, b
bnz B, t

sub b, b, a
jmp C

B:
sub a, a, b

C:
jmp A
```



Part IV

Assembly Code and Assemblers

Assembly Code

Most compilers produce assembly code: easy to debug.

```
! gcd on the SPARC
gcd:
    cmp   %o0, %o1
    be    .LL8
    nop
.LL9:
    ble,a .LL2
    sub   %o1, %o0, %o1
    sub   %o0, %o1, %o0
.LL2:
    cmp   %o0, %o1
    bne   .LL9
    nop
.LL8:
    retl
    nop
```

Comment

Opcode

Operand (a register)

Label

Conditional branch to a label

No operation

Role of an Assembler

Translate opcodes + operand into byte codes

Address

Instruction code

```
                gcd:
0000 80A20009          cmp   %o0, %o1
0004 02800008          be    .LL8
0008 01000000          nop
                .LL9:
000c 24800003          ble,a .LL2
0010 92224008          sub   %o1, %o0, %o1
0014 90220009          sub   %o0, %o1, %o0
                .LL2:
0018 80A20009          cmp   %o0, %o1
001c 12BFFFFC          bne   .LL9
0020 01000000          nop
                .LL8:
0024 81C3E008          retl
0028 01000000          nop
```

Encoding Example

```
sub   %o1, %o0, %o1
```

Encoding of “SUB” on the SPARC:

10	rd	000100	rs1	0	reserved	rs2
31	29	24	18	13	12	4

rd = %o1 = 01001

rs1 = %o1 = 01001

rs2 = %o0 = 00100

10 01001 000100 01001 0 00000000 01000
1001 0010 0010 0010 0100 0000 0000 1000

= 0x92228004

Role of an Assembler

Transforming symbolic addresses to concrete ones.

Example: Calculating PC-relative branch offsets.

LL2 is 3 words away

```
000c 24800003        ble,a .LL2
0010 92224008        sub   %o1, %o0, %o1
0014 90220009        sub   %o0, %o1, %o0
              .LL2:
0018 80A20009        cmp   %o0, %o1
```

Role of an Assembler

Most assemblers are "two-pass" because they can't calculate everything in a single pass through the code.

```
               .LL9:
000c 24800003      ble,a .LL2
0010 92224008      sub   %o1, %o0, %o1
0014 90220009      sub   %o0, %o1, %o0
               .LL2:
0018 80A20009      cmp   %o0, %o1
001c 12BFFFFC      bne   .LL9
```

Don't know offset of LL2

Know offset of LL9

Role of an Assembler

Constant data needs to be aligned.

```
char a[] = "Hello";
int b[3] = { 5, 6, 7 };
```

Assembler directive

```
                .section ".data"    ! "This is data"
                .global a           ! "Let other files see a
                .type   a,#object   ! "a is a variable"
                .size   a,6         ! "six bytes long"
            a:
0000 48656C6C   .asciz  "Hello"     ! zero-terminated ASCII
     6F00
                .global b
0006 0000       .align 4
                .type   b,#object
                .size   b,12
            b:
0008 00000005   .uaword 5
000c 00000006   .uaword 6
0010 00000007   .uaword 7
```

Bytes added to ensure alignment

Role of an Assembler

The MIPS has pseudoinstructions:

"Load the immediate value 0x12345abc into register 14:"

```
li $14, 0x12345abc
```

expands to

```
lui $14, 0x1234
ori $14, 0x5abc
```

"Load the upper 16 bits, then OR in the lower 16"

MIPS instructions have 16-bit immediate values at most

RISC philosophy: small instructions for common case

Part V

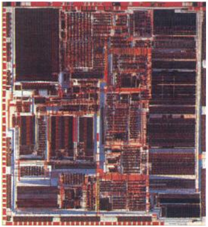
Optimization: Register Allocation

Optimization: Register Allocation

Where to put temporary results? The easiest is to put everything on the stack.

```
int bar(int g, int h, int i,
        int j, int k, int l)
{
  int a, b, c, d, e, f;
  a = foo(g);
  b = foo(h);
  c = foo(i);
  d = foo(j);
  e = foo(k);
  f = foo(l);
  return a + b + c + d + e + f;
}
```

Quick Review of the x86 Architecture



Eight "general-purpose" 32-bit registers:

eax ebx ecx edx ebp esi edi esp

esp is the stack pointer

ebp is the base (frame) pointer

`addl %eax, %edx` eax + edx → edx

Base-pointer-relative addressing:

`movl 20(%ebp), %eax` Load word at ebp+20 into eax

Unoptimized GCC on the x86

```
movl 24(%ebp),%eax   % Get k
pushl %eax           % Push argument
call foo             % e = foo(k);
addl $4,%esp         % Make room for e
movl %eax,%eax       % Does nothing
movl %eax,-20(%ebp)  % Save return value on stack

movl 28(%ebp),%eax   % Get l
pushl %eax           % Push argument
call foo             % f = foo(l);
addl $4,%esp         % Make room for f
movl %eax,%eax       % Does nothing
movl %eax,-24(%ebp)  % Save return value on stack

movl -20(%ebp),%eax  % Get f
movl -24(%ebp),%edx  % Get e
addl %edx,%eax       % e + f
movl %eax,%edx       % Accumulate in edx
addl -16(%ebp),%edx  % d + (e+f)
movl %edx,%eax       % Accumulate in edx
```

```
int bar(int g, int h, int i,
        int j, int k, int l)
{
  int a, b, c, d, e, f;
  a = foo(g);
  b = foo(h);
  c = foo(i);
  d = foo(j);
  e = foo(k);
  f = foo(l);
  return a + b + c + d + e + f;
}
```

Optimized GCC on the x86

```
movl 20(%ebp),%edx   % Get j
pushl %edx           % Push argument
call foo             % d = foo(j);
movl %eax,%esi       % save d in esi

movl 24(%ebp),%edx   % Get k
pushl %edx           % Push argument
call foo             % e = foo(k);
movl %eax,%ebx       % save e in ebx

movl 28(%ebp),%edx   % Get l
pushl %edx           % Push argument
call foo             % f = foo(l);

addl %ebx,%eax       % e + f
addl %esi,%eax       % d + (e+f)
```

```
int bar(int g, int h, int i,
        int j, int k, int l)
{
  int a, b, c, d, e, f;
  a = foo(g);
  b = foo(h);
  c = foo(i);
  d = foo(j);
  e = foo(k);
  f = foo(l);
  return a + b + c + d + e + f;
}
```

Unoptimized vs. Optimized

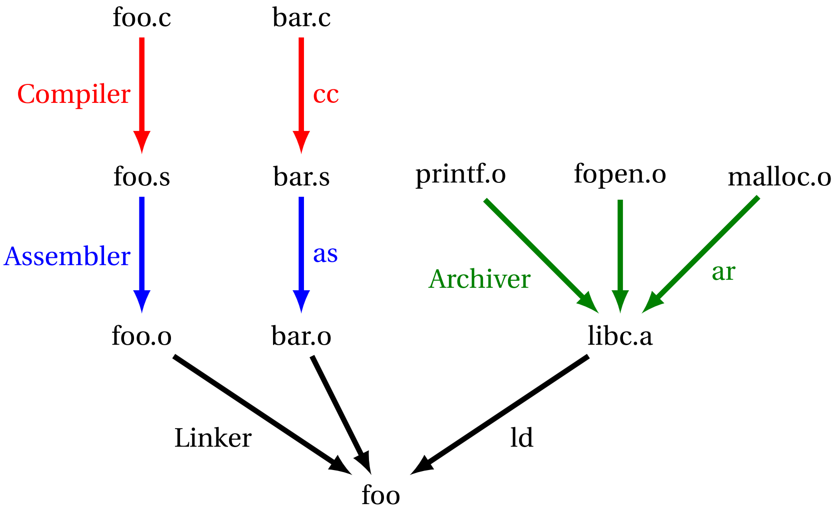
```
                          movl 20(%ebp),%edx
                          pushl %edx
                          call foo
                          movl %eax,%esi

movl 24(%ebp),%eax        movl 24(%ebp),%edx
pushl %eax                pushl %edx
call foo                  call foo
addl $4,%esp              movl %eax,%ebx
movl %eax,%eax
movl %eax,-20(%ebp)

movl 28(%ebp),%eax        movl 28(%ebp),%edx
pushl %eax                pushl %edx
call foo                  call foo
addl $4,%esp
movl %eax,%eax
movl %eax,-24(%ebp)

movl -20(%ebp),%eax
movl -24(%ebp),%edx
addl %edx,%eax            addl %ebx,%eax
movl %eax,%edx
addl -16(%ebp),%edx       addl %esi,%eax
movl %edx,%eax
```

```c
int bar(int g, int h, int i,
        int j, int k, int l)
{
  int a, b, c, d, e, f;
  a = foo(g);
  b = foo(h);
  c = foo(i);
  d = foo(j);
  e = foo(k);
  f = foo(l);
  return a + b + c + d + e + f;
}
```

Part VI

Separate Compilation and Linking

Separate Compilation and Linking



Linking

Goal of the linker is to combine the disparate pieces of the program into a coherent whole.

file1.c:

```
#include <stdio.h>
char a[] = "Hello";
extern void bar();

int main() {
  bar();
}

void baz(char *s) {
  printf("%s", s);
}
```

file2.c:

```
#include <stdio.h>
extern char a[];

static char b[6];

void bar() {
  strcpy(b, a);
  baz(b);
}
```

libc.a:

```
int
printf(char *s, ...)
{
  /* ... */
}

char *
strcpy(char *d,
       char *s)
{
  /* ... */
}
```

Linking

Goal of the linker is to combine the disparate pieces of the program into a coherent whole.

file1.c:

```
#include <stdio.h>
char a[] = "Hello";
extern void bar();

int main() {
  bar();
}

void baz(char *s) {
  printf("%s", s);
}
```

file2.c:

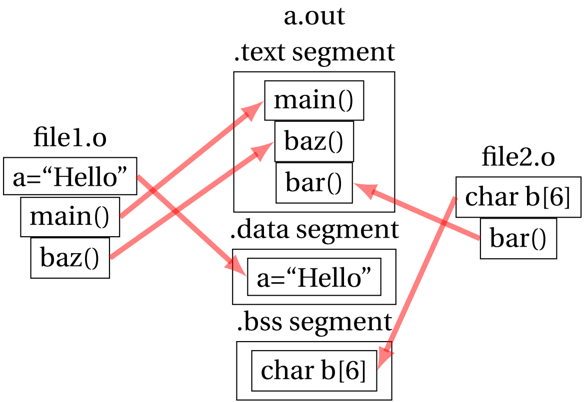
```
#include <stdio.h>
extern char a[];

static char b[6];

void bar() {
  strcpy(b, a);
  baz(b);
}
```

libc.a:

```
int
printf(char *s, ...)
{
  /* ... */
}

char *
strcpy(char *d,
       char *s)
{
  /* ... */
}
```

Linking

Linking



.text
Code of program

.data
Initialized data

.bss
Uninitialized data
"Block Started by Symbol"

Object Files

Relocatable: Many need to be pasted together. Final in-memory address of code not known when program is compiled

Object files contain

- imported symbols (unresolved “external” symbols)
- relocation information (what needs to change)
- exported symbols (what other files may refer to)

Object Files

file1.c:

```
#include <stdio.h>
char a[] = "Hello";
extern void bar();

int main() {
  bar();
}

void baz(char *s) {
  printf("%s", s);
}
```

exported symbols

imported symbols

Object Files

file1.c:

```
#include <stdio.h>
char a[] = "Hello";
extern void bar();

int main() {
  bar();
}

void baz(char *s) {
  printf("%s", s);
}
```

```
# objdump -x file1.o
Sections:
Idx Name    Size VMA LMA Offset Algn
  0 .text   038  0   0   034    2**2
  1 .data   008  0   0   070    2**3
  2 .bss    000  0   0   078    2**0
  3 .rodata 008  0   0   078    2**3

SYMBOL TABLE:
0000 g O .data   006 a
0000 g F .text   014 main
0000     *UND*   000 bar
0014 g F .text   024 baz
0000     *UND*   000 printf

RELOCATION RECORDS FOR [.text]:
OFFSET   TYPE           VALUE
0004 R_SPARC_WDISP30   bar
001c R_SPARC_HI22      .rodata
0020 R_SPARC_LO10      .rodata
0028 R_SPARC_WDISP30   printf
```

Object Files

file1.c:

```c
#include <stdio.h>
char a[] = "Hello";
extern void bar();

int main() {
  bar();
}

void baz(char *s) {
  printf("%s", s);
}
```

```
# objdump -d file1.o
0000 <main>:
 0: 9d e3 bf 90 save  %sp, -112, %sp
 4: 40 00 00 00 call  4 <main+0x4>
    4: R_SPARC_WDISP30 bar
 8: 01 00 00 00 nop
 c: 81 c7 e0 08 ret
10: 81 e8 00 00 restore

0014 <baz>:
14: 9d e3 bf 90 save  %sp, -112, %sp
18: f0 27 a0 44 st  %i0, [ %fp + 0x44 ]
1c: 11 00 00 00 sethi  %hi(0), %o0
    1c: R_SPARC_HI22 .rodata
20: 90 12 20 00 mov  %o0, %o0
    20: R_SPARC_LO10 .rodata
24: d2 07 a0 44 ld  [ %fp + 0x44 ], %o1
28: 40 00 00 00 call  28 <baz+0x14>
    28: R_SPARC_WDISP30 printf
2c: 01 00 00 00 nop
30: 81 c7 e0 08 ret
34: 81 e8 00 00 restore
```

Before and After Linking

```
int main() {
  bar();
}

void baz(char *s) {
  printf("%s", s);
}
```

- Combine object files
- Relocate each function's code
- Resolve previously unresolved symbols

```
0000 <main>:
 0: 9d e3 bf 90 save  %sp, -112, %sp
 4: 40 00 00 00 call  4 <main+0x4>
    4: R_SPARC_WDISP30 bar
 8: 01 00 00 00 nop
 c: 81 c7 e0 08 ret
10: 81 e8 00 00 restore

0014 <baz>:
14: 9d e3 bf 90 save  %sp, -112, %sp
18: f0 27 a0 44 st  %i0, [ %fp + 0x44 ]
1c: 11 00 00 00 sethi  %hi(0), %o0
    1c: R_SPARC_HI22 .rodata
20: 90 12 20 00 mov  %o0, %o0
    20: R_SPARC_LO10 .rodata
24: d2 07 a0 44 ld  [ %fp + 0x44 ], %o1
28: 40 00 00 00 call  28 <baz+0x14>
    28: R_SPARC_WDISP30 printf
2c: 01 00 00 00 nop
30: 81 c7 e0 08 ret
34: 81 e8 00 00 restore
```

Unresolved symbol

Code starting address changed

```
105f8 <main>:
105f8: 9d e3 bf 90 save %sp, -112, %sp
105fc: 40 00 00 0d call 10630 <bar>

10600: 01 00 00 00 nop
10604: 81 c7 e0 08 ret
10608: 81 e8 00 00 restore

1060c <baz>:
1060c: 9d e3 bf 90 save  %sp, -112, %sp
10610: f0 27 a0 44 st    %i0, [ %fp + 0x44 ]
10614: 11 00 00 41 sethi %hi(0x10400), %o0

10618: 90 12 23 00 or    %o0, 0x300, %o0

1061c: d2 07 a0 44 ld    [ %fp + 0x44 ], %o1
10620: 40 00 40 62 call  207a8

10624: 01 00 00 00 nop
10628: 81 c7 e0 08 ret
1062c: 81 e8 00 00 restore
```

Linking Resolves Symbols

file1.c:

```
#include <stdio.h>
char a[] = "Hello";
extern void bar();

int main() {
  bar();
}

void baz(char *s) {
  printf("%s", s);
}
```

file2.c:

```
#include <stdio.h>
extern char a[];

static char b[6];

void bar() {
  strcpy(b, a);
  baz(b);
}
```

```
105f8 <main>:
105f8: 9d e3 bf 90 save %sp, -112, %sp
105fc: 40 00 00 0d call 10630 <bar>
10600: 01 00 00 00 nop
10604: 81 c7 e0 08 ret
10608: 81 e8 00 00 restore

1060c <baz>:
1060c: 9d e3 bf 90 save  %sp, -112, %sp
10610: f0 27 a0 44 st    %i0, [ %fp + 0x44 ]
10614: 11 00 00 41 sethi %hi(0x10400), %o0
10618: 90 12 23 00 or    %o0, 0x300, %o0    ! "%s"
1061c: d2 07 a0 44 ld    [ %fp + 0x44 ], %o1
10620: 40 00 40 62 call  207a8              ! printf
10624: 01 00 00 00 nop
10628: 81 c7 e0 08 ret
1062c: 81 e8 00 00 restore

10630 <bar>:
10630: 9d e3 bf 90 save  %sp, -112, %sp
10634: 11 00 00 82 sethi %hi(0x20800), %o0
10638: 90 12 20 a8 or    %o0, 0xa8, %o0     ! 208a8 <b>
1063c: 13 00 00 81 sethi %hi(0x20400), %o1
10640: 92 12 63 18 or    %o1, 0x318, %o1    ! 20718 <a>
10644: 40 00 40 4d call  20778              ! strcpy
10648: 01 00 00 00 nop
1064c: 11 00 00 82 sethi %hi(0x20800), %o0
10650: 90 12 20 a8 or    %o0, 0xa8, %o0     ! 208a8 <b>
10654: 7f ff ff ee call  1060c <baz>
10658: 01 00 00 00 nop
1065c: 81 c7 e0 08 ret
10660: 81 e8 00 00 restore
10664: 81 c3 e0 08 retl
10668: ae 03 c0 17 add  %o7, %l7, %l7
```

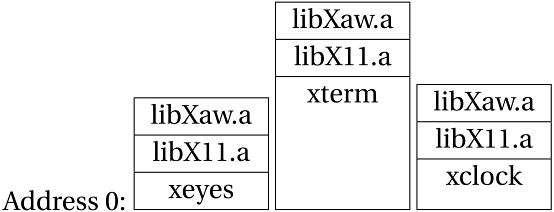
Part VII

Shared Libraries and Dynamic Linking

Shared Libraries and Dynamic Linking

The 1980s GUI/WIMP revolution required many large libraries (the Athena widgets, Motif, etc.)

Under a *static linking* model, each executable using a library gets a copy of that library's code.



Shared Libraries and Dynamic Linking

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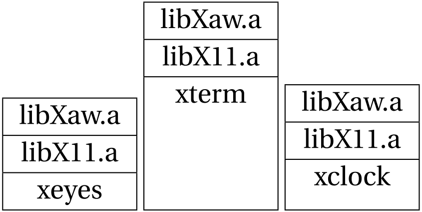
Under a *static linking* model, each executable using a library gets a copy of that library's code.

Address 0:



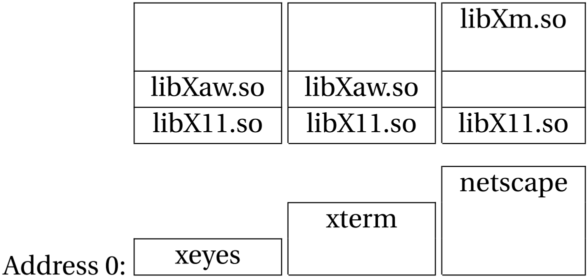
Wasteful: running many GUI programs at once fills memory with nearly identical copies of each library.

Something had to be done: another level of indirection.

Shared Libraries: First Attempt

Most code makes assumptions about its location.

First solution (early Unix System V R3) required each shared library to be located at a unique address:



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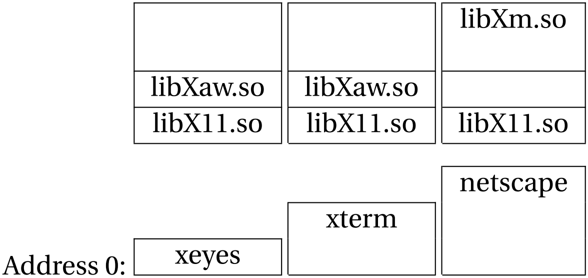
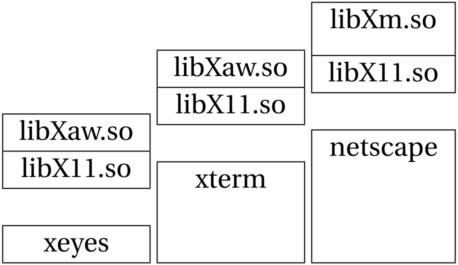


Obvious disadvantage: must ensure each new shared library located at a new address.

Works fine if there are only a few libraries; tended to discourage their use.

Shared Libraries

Problem fundamentally is that each program may need to see different libraries each at a different address.



Position-Independent Code

Solution: Require the code for libraries to be position-independent.
Make it so they can run anywhere in memory.

As always, add another level of indirection:

- All branching is PC-relative
- All data must be addressed relative to a base register.
- All branching to and from this code must go through a jump table.

Position-Independent Code for bar()

Normal unlinked code

```
save  %sp, -112, %sp
sethi  %hi(0), %o0
  R_SPARC_HI22 .bss
mov  %o0, %o0
  R_SPARC_LO10 .bss
sethi  %hi(0), %o1
  R_SPARC_HI22 a
mov  %o1, %o1
  R_SPARC_LO10 a
call  14
  R_SPARC_WDISP30 strcpy
nop
sethi  %hi(0), %o0
  R_SPARC_HI22 .bss
mov  %o0, %o0
  R_SPARC_LO10 .bss
call  24
  R_SPARC_WDISP30 baz
nop
ret
restore
```

gcc -fpic -shared

```
save  %sp, -112, %sp
sethi  %hi(0x10000), %l7
call  8e0   ! add PC to %l7
add  %l7, 0x198, %l7
ld  [ %l7 + 0x20 ], %o0
ld  [ %l7 + 0x24 ], %o1

call  10a24 ! strcpy

nop
ld  [ %l7 + 0x20 ], %o0

call  10a3c ! baz

nop
ret
restore
```

Actually just a stub

call is PC-relative