6.035

Unoptimized Code Generation

Orientation

- Source code
- Intermediate representation
- Unoptimized assembler
- Executable file
  - Data segments (initialized, zeroed, constant)
  - Code segments

Big Picture

- Starting point – Intermediate Representation
- Ending point – Generated Assembly Code

- Emphasis on UNOPTIMIZED
- Do simplest possible thing for now
- Will treat optimizations separately

Machines understand...

LOCATION	DATA
0046	8B45FC
0049	4863F0
004c	8B45FC
004f	4863D0
0052	8B45FC
0055	4898
0057	8B048500
	000000
005e	8B149500
	000000
0065	01C2
0067	8B45FC
006a	4898
006c	89D7
006e	033C8500
	000000
0075	8B45FC
0078	4863C8
007b	8B45F8
007e	4898
0080	8B148500

Machines understand...

LOCATION	DATA	ASSEMBLY INSTRUCTION
0046	8B45FC	movl -4(%rbp), %eax
0049	4863F0	movslq %eax,%rsi
004c	8B45FC	movl -4(%rbp), %eax
004f	4863D0	movslq %eax,%rdx
0052	8B45FC	movl -4(%rbp), %eax
0055	4898	cltq
0057	8B048500 000000	movl B(,%rax,4), %eax
005e	8B149500 000000	movl A(,%rdx,4), %edx
0065	01C2	addl %eax, %edx
0067	8B45FC	movl -4(%rbp), %eax
006a	4898	cltq
006c	89D7	movl %edx, %edi
006e	033C8500 000000	addl C(,%rax,4), %edi
0075	8B45FC	movl -4(%rbp), %eax
0078	4863C8	movslq %eax,%rcx
007b	8B45F8	movl -8(%rbp), %eax
007e	4898	cltq
0080	8B148500	movl B(,%rax,4), %edx

Assembly language

- Advantages
  - Simplifies code generation due to use of symbolic instructions and symbolic names
  - Logical abstraction layer
  - Many different architectures implement same ISA
- Disadvantages
  - Additional process of assembling and linking
  - Assembler adds overhead

Assembly language

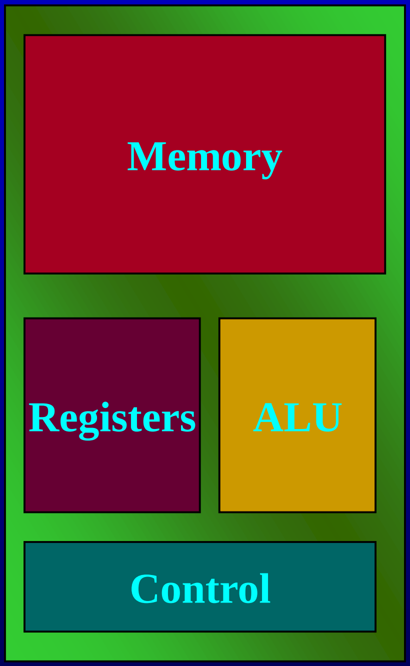
- Relocatable machine language (object modules)
  - all locations(addresses) represented by symbols
  - Mapped to memory addresses at link and load time
  - Flexibility of separate compilation
- Absolute machine language
  - addresses are hard-coded
  - simple and straightforward implementation
  - inflexible -- hard to reload generated code
  - Used in interrupt handlers and device drivers

Concept of An Object File

- The object file has:
  - Multiple Segments
  - Symbol Information
  - Relocation Information
- Segments
  - Global Offset Table
  - Procedure Linkage Table
  - Text (code)
  - Data
  - Read Only Data
- To run program, OS reads object file, builds executable process in memory, runs process
- We will use assembler to generate object files

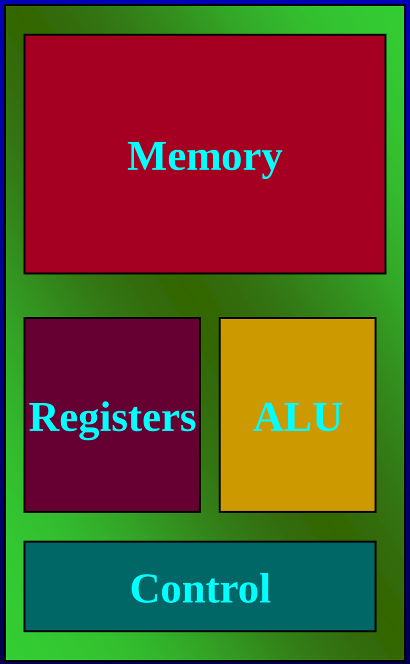
Overview of a modern ISA

- Memory
- Registers
- ALU
- Control

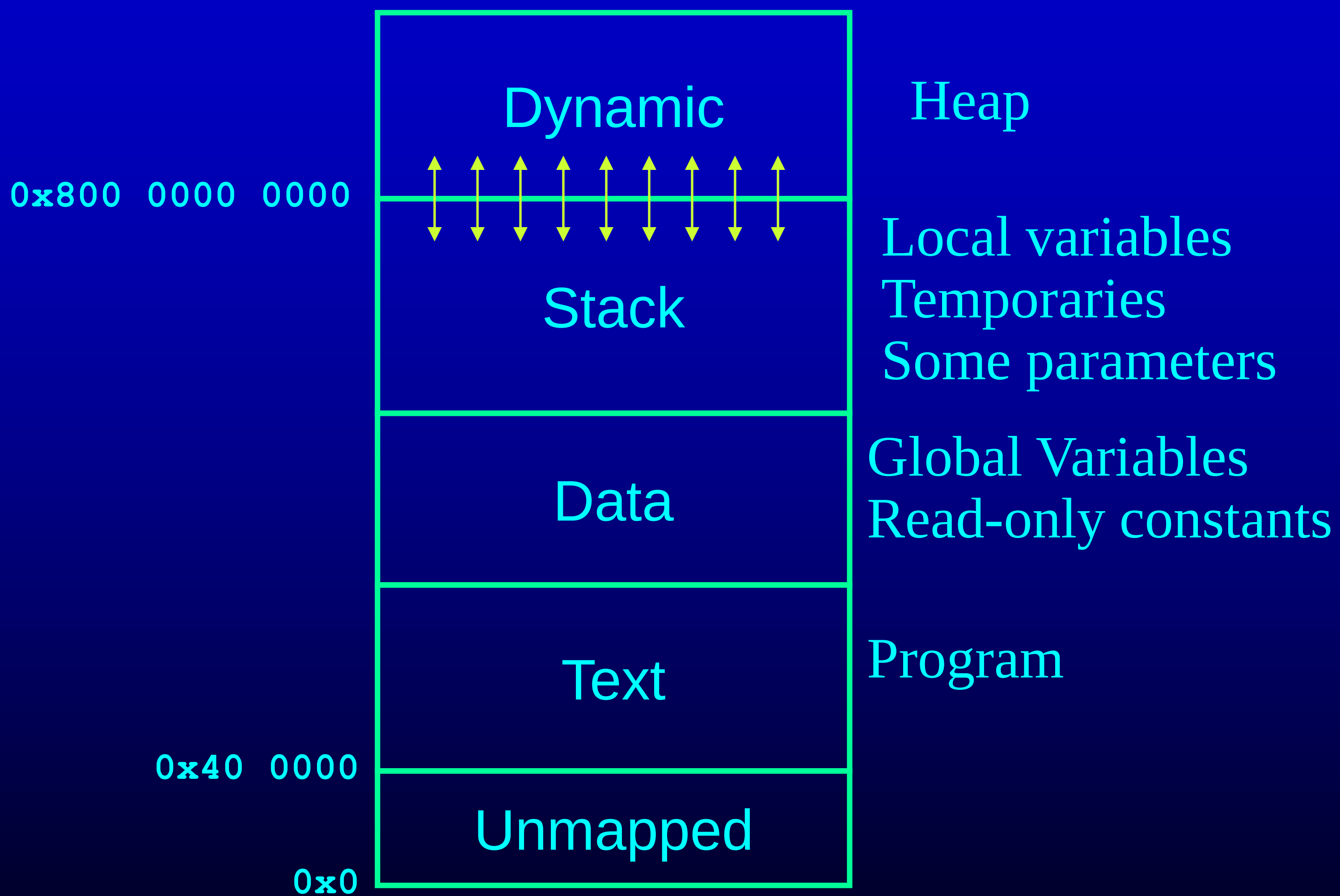


From IR to Assembly

- Data Placement and Layout
  - Global variables
  - Constants (strings, numbers)
  - Object fields
  - Parameters, local variables
  - Temporaries
- Code
  - Read and write data
  - Compute
  - Flow of control



Typical Memory Layout



Generated Assembler

```
int a[10];
int count;
```

```
.bss
.global_count:
    .zero 8
.global_a:
    .zero 80
```

Example (Illustrative, Not Definitive)

```
int PlusOne(int p) {
  int t;
  t = 1;
  return p+t;
}
```

```
.method_PlusOne:
    PUSH_ALL_REGS
    subq $48, %rsp
    movq 128(%rsp), %rax
    movq %rax, 40(%rsp)
.node_41:
    movq 40(%rsp), %rax
    movq %rax, 32(%rsp)
    movq $0, 24(%rsp)
    movq $1, 24(%rsp)
    movq 32(%rsp), %rax
    movq %rax, 16(%rsp)
    movq 24(%rsp), %rax
    movq %rax, 8(%rsp)
    movq 16(%rsp), %rax
    addq 8(%rsp), %rax
    movq %rax, (%rsp)
    movq (%rsp), %rax
    movq %rax, 160(%rsp)
    addq $48, %rsp
    POP_ALL_REGS
    ret
```

```
int increment() {
  count = count  + 1;
  return count;
}
```

```
.method_increment:
    PUSH_ALL_REGS
    subq $24, %rsp
.node_61:
    movq .global_count, %rax
    movq %rax, 16(%rsp)
    movq 16(%rsp), %rax
    addq $1, %rax
    movq %rax, 8(%rsp)
    movq 8(%rsp), %rax
    movq %rax, .global_count
    movq .global_count, %rax
    movq %rax, (%rsp)
    movq (%rsp), %rax
    movq %rax, 136(%rsp)
    addq $24, %rsp
    POP_ALL_REGS
    ret
```

```c
int sign(int p) {
  if (p < 0) {
    return -1;
  } else {
  if (p > 0) {
    return 1;
  } else {
    return 0;
  }
  }
}
```

```asm
.method_sign:
    PUSH_ALL_REGS
    subq $48, %rsp
    movq 128(%rsp), %rax
    movq %rax, 40(%rsp)
.node_110:
    movq 40(%rsp), %rax
    movq %rax, 32(%rsp)
    movq 32(%rsp), %rax
    movq %rax, 24(%rsp)
    cmpq $0, 24(%rsp)
    movq $0, %rax
    setl %al
    movq %rax, 16(%rsp)
    cmpq $0, 24(%rsp)
    jl .node_111
    jmp .node_112
.node_112:
    movq 32(%rsp), %rax
    movq %rax, 8(%rsp)
    cmpq $0, 8(%rsp)
    movq $0, %rax
    setg %al
    movq %rax, (%rsp)
    movq $0, %rax
    cmpq 8(%rsp), %rax
    jl .node_113
    jmp .node_114
```

```c
int sign(int p) {
  if (p < 0) {
    return -1;
  } else {
  if (p > 0) {
    return 1;
  } else {
    return 0;
  }
  }
}
```

```
.node_114:
    movq $0, 160(%rsp)
    addq $48, %rsp
    POP_ALL_REGS
    ret
.node_113:
    movq $1, 160(%rsp)
    addq $48, %rsp
    POP_ALL_REGS
    ret
.node_111:
    movq $-1, 160(%rsp)
    addq $48, %rsp
    POP_ALL_REGS
    ret
```

Exploring Assembly Patterns

```
struct { int x, y; double z; } b;
int g;
int a[10];
char *s = "Test String”;
int f(int p) {
  int i;
  int s;
  s = 0.0;
  for (i = 0; i < 10; i++) {
    s = s + a[i];
  }
  return s;
}
```

- gcc –g –S t.c
- vi t.s

Global Variables

C

```
struct { int x, y; double z; } b;
int g;
int a[10];
```

Assembler directives (reserve space in data segment)

```
.comm   _a,40,4        ## @a
.comm   _b,16,3        ## @b
.comm   _g,4,2         ## @g
```

Name (`_g`) **Size** (`4`) **Alignment** (`2`)

Addresses

Reserve Memory

```
.comm   _a,40,4          ## @a
.comm   _b,16,3          ## @b
.comm   _g,4,2           ## @g
```

Define 3 constants

- _a – address of a in data segment
- _b – address of b in data segment
- _g – address of g in data segment

Struct and Array Layout

- struct { int x, y; double z; } b;
  - Bytes 0-1: x
  - Bytes 2-3: y
  - Bytes 4-7: z
- int a[10]
  - Bytes 0-1: a[0]
  - Bytes 2-3: a[1]
  - …
  - Bytes 18-19: a[9]

Dynamic Memory Allocation

```
typedef struct { int x, y; } PointStruct, *Point;
Point p = malloc(sizeof(PointStruct));
```

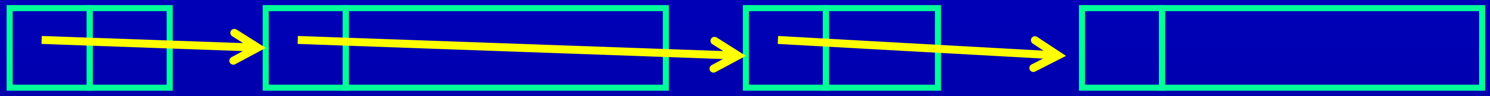
What does allocator do?

returns next free big enough data block in heap

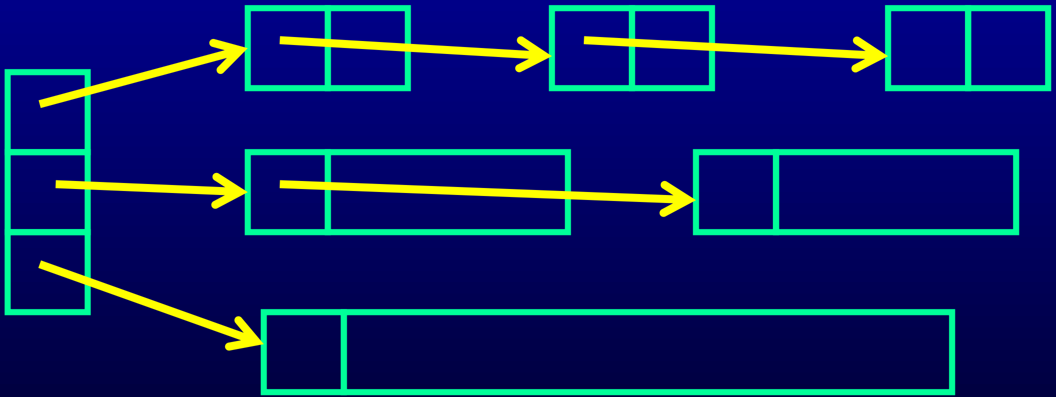
appropriately adjusts heap data structures

Some Heap Data Structures

- Free List (arrows are addresses)



- Powers of Two Lists

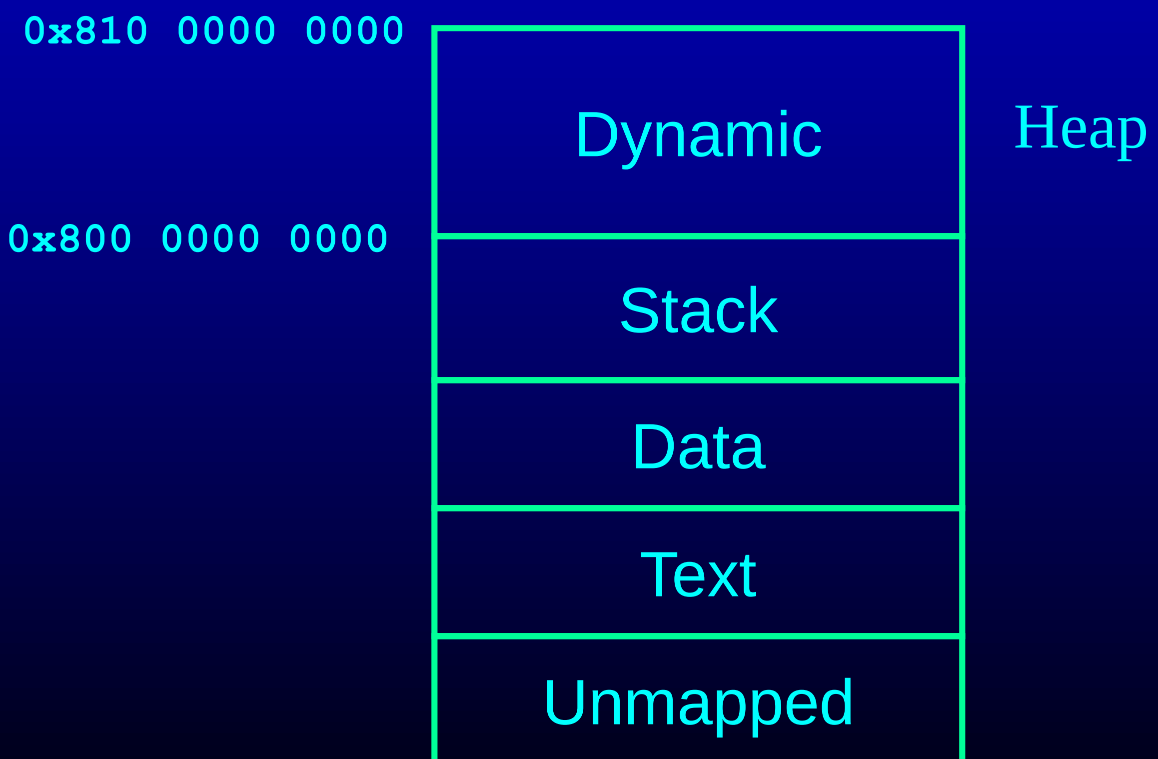


Getting More Heap Memory

Scenario: Current heap goes from `0x800 0000 000- 0x810 0000 0000`

Need to allocate large block of memory

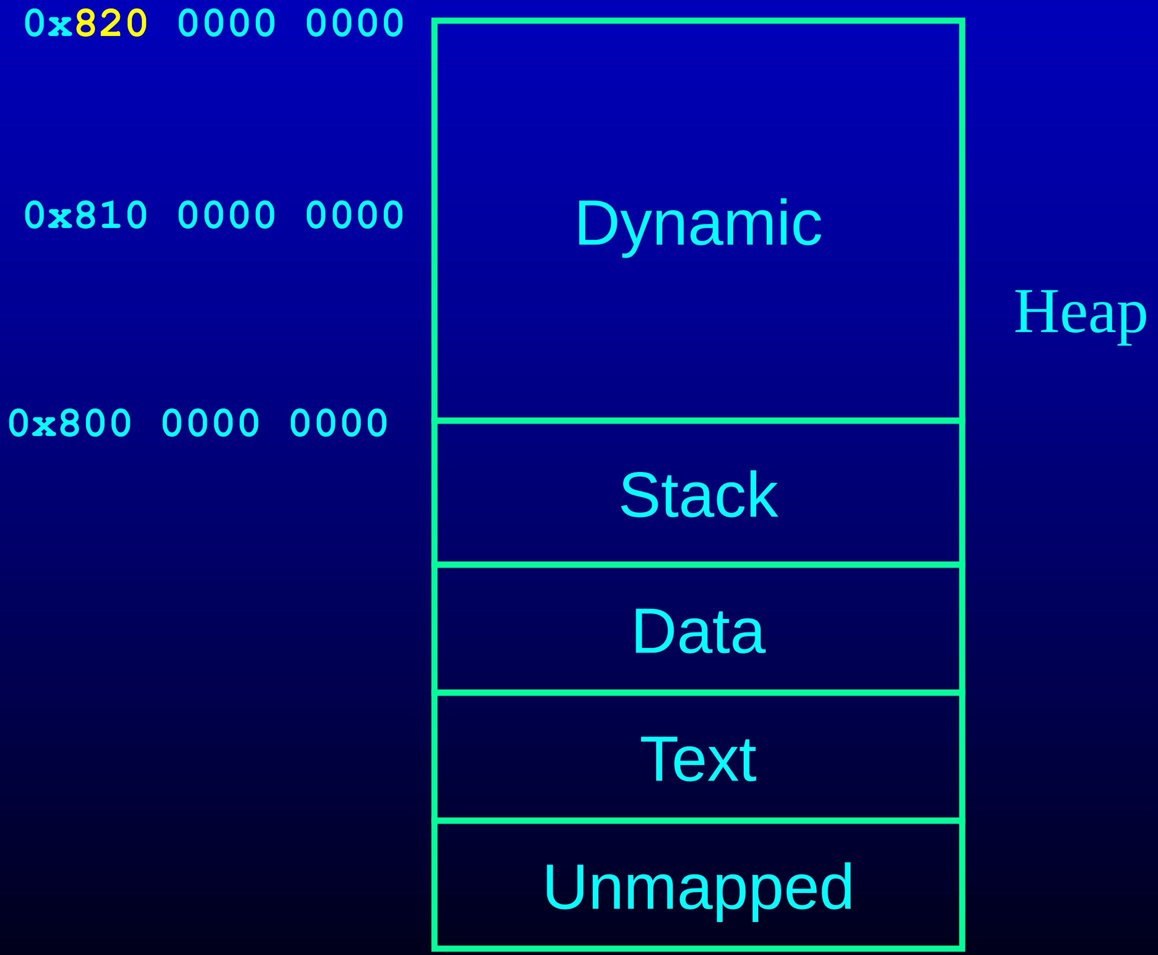
No block that large available



Getting More Heap Memory

Solution: Talk to OS, increase size of heap (sbrk)

Allocate block in new heap



The Stack

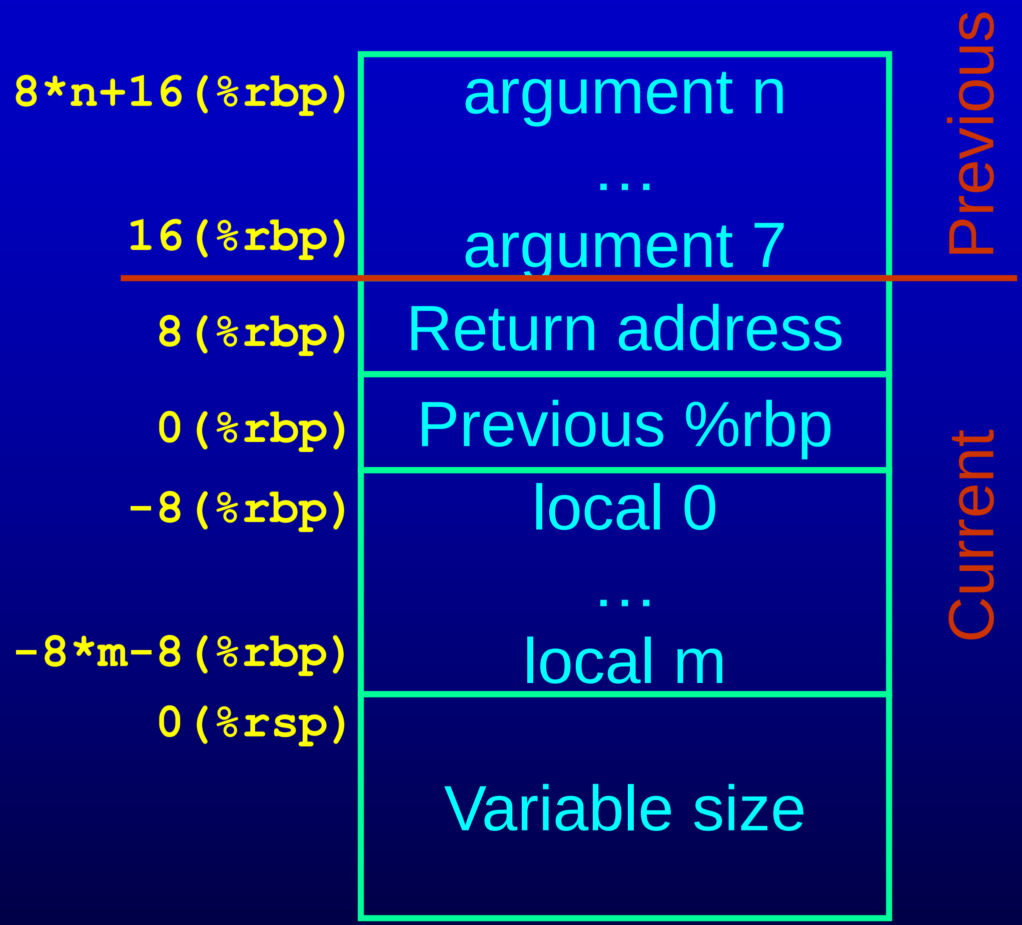
- Arguments 0 to 6 are in:
  - %rdi, %rsi, %rdx,
  - %rcx, %r8 and %r9

%rbp

- marks the beginning of the current frame

%rsp

- marks the end

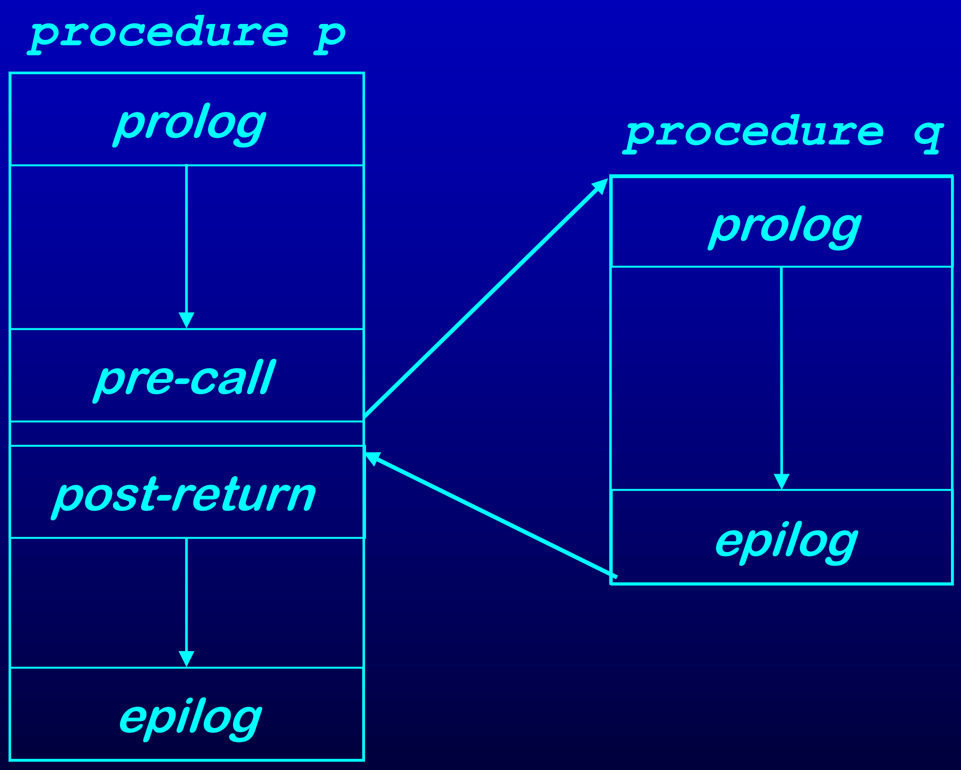


Question:

- Why use a stack? Why not use the heap or pre-allocated in the data segment?

Procedure Linkages

Standard procedure linkage



Pre-call:

- Save caller-saved registers
- Push arguments

Prolog:

- Push old frame pointer
- Save callee-saved registers
- Make room for temporaries

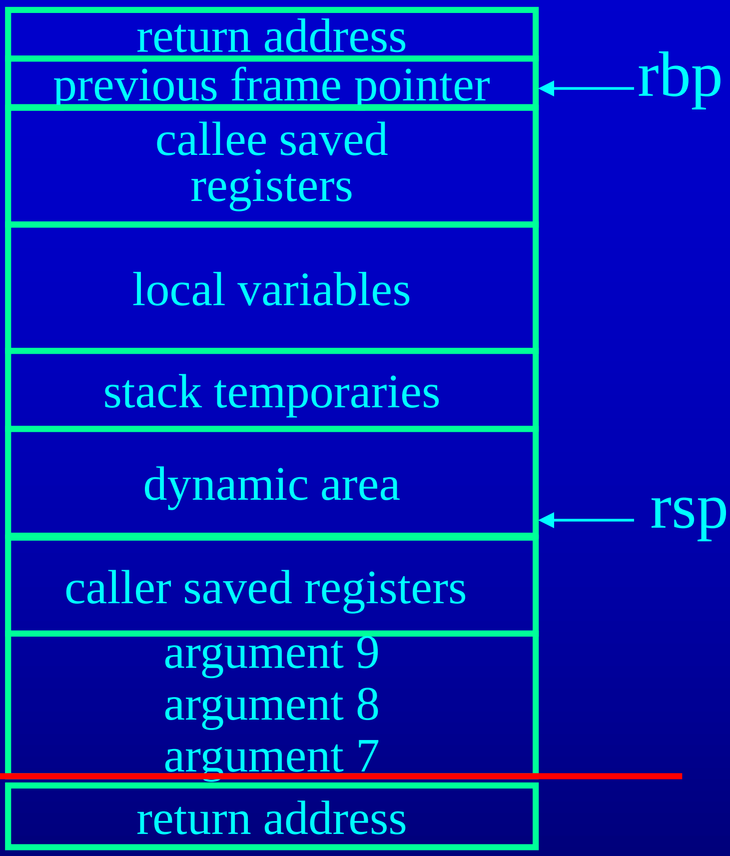
Epilog:

- Restore callee-saved
- Pop old frame pointer
- Store return value

Post-return:

- Restore caller-saved
- Pop arguments

Stack



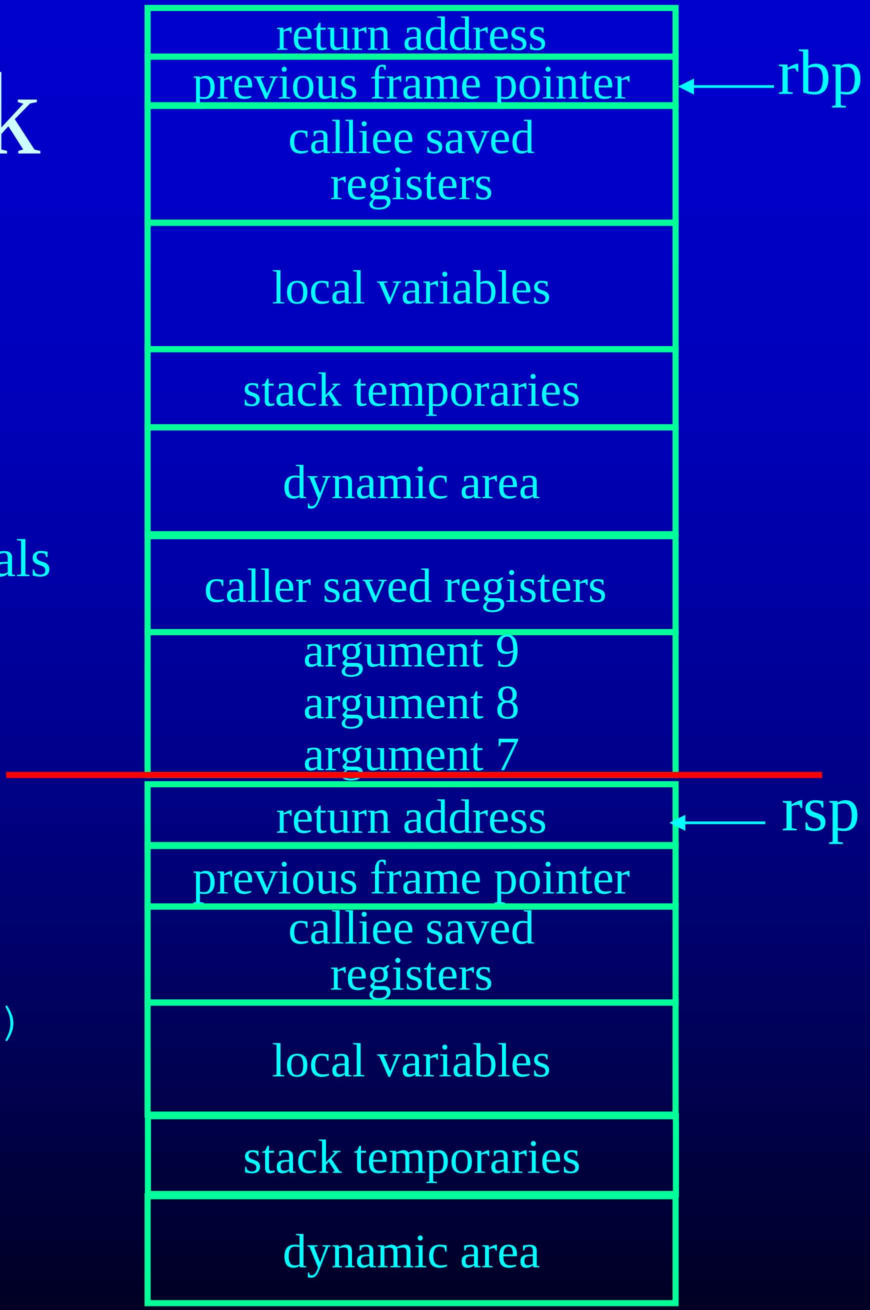
- Calling: Caller
  - Assume %rcx is live and is caller save
  - Call foo(A, B, C, D, E, F, G, H, I)
    - A to I are at -8(%rbp) to -72(%rbp)

```
push        %rcx
push        -72(%rbp)
push        -64(%rbp)
push        -56(%rbp)
mov          -48(%rbp), %r9
mov          -40(%rbp), %r8
mov          -32(%rbp), %rcx
mov          -24(%rbp), %rdx
mov          -16(%rbp), %rsi
mov          -8(%rbp), %rdi
call        foo
```

Stack

- Calling: Callee
  - Assume %rbx is used in the function and is callee save
  - Assume 40 bytes are required for locals

```
foo:
    push    %rbp
    mov     %rsp, %rbp
    enter   $48, $0
    sub     $48, %rsp
    mov     %rbx, -8(%rbp)
```



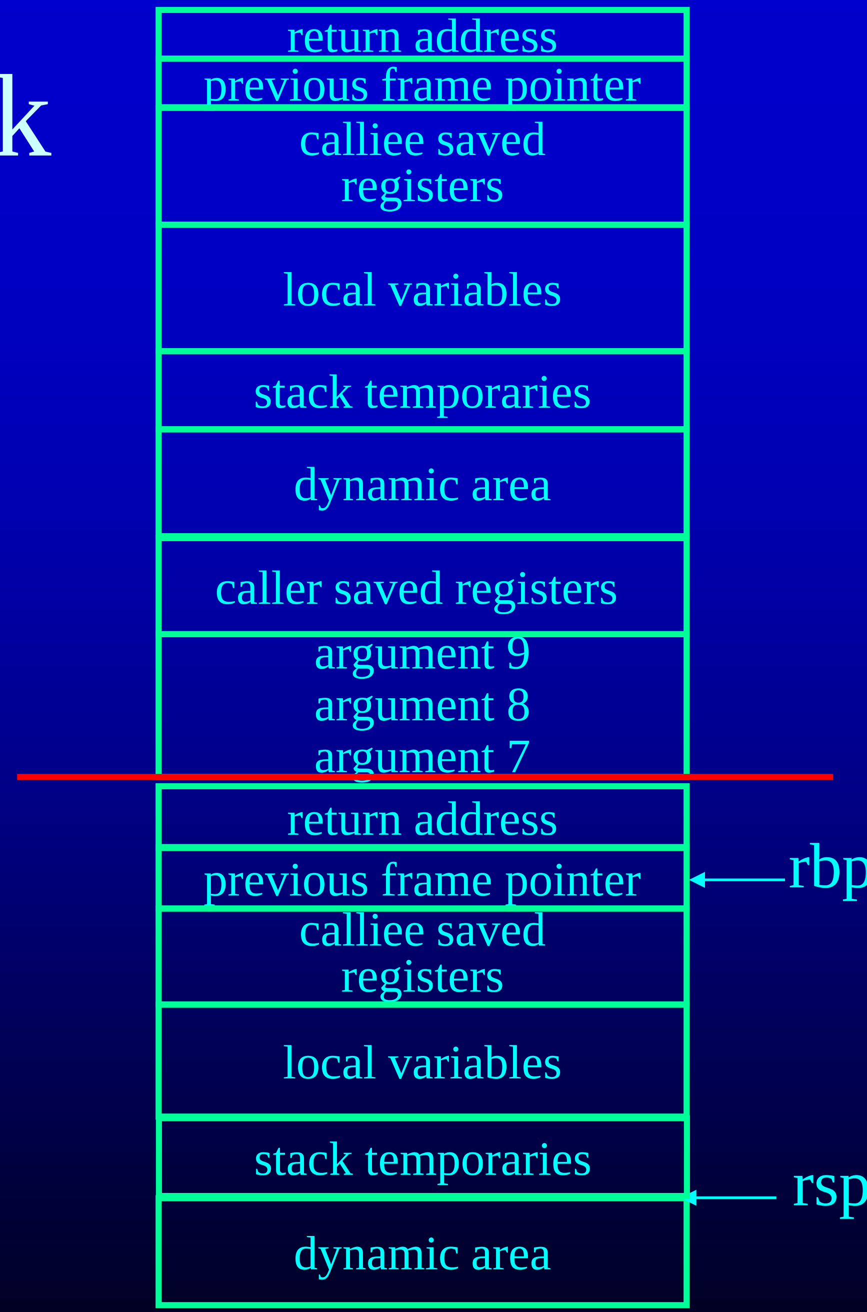
Stack

- Arguments
- Call foo(A, B, C, D, E, F, G, H, I)
  - Passed in by pushing before the call

```
push    -72(%rbp)
push    -64(%rbp)
push    -56(%rbp)
mov     -48(%rbp), %r9
mov     -40(%rbp), %r8
mov     -32(%rbp), %rcx
mov     -24(%rbp), %rdx
mov     -16(%rbp), %rsi
mov     -8(%rbp), %rdi
call    foo
```

  - Access A to F via registers
    - or put them in local memory
  - Access rest using 16+xx(%rbp)

```
mov     16(%rbp), %rax
mov     24(%rbp), %r10
```



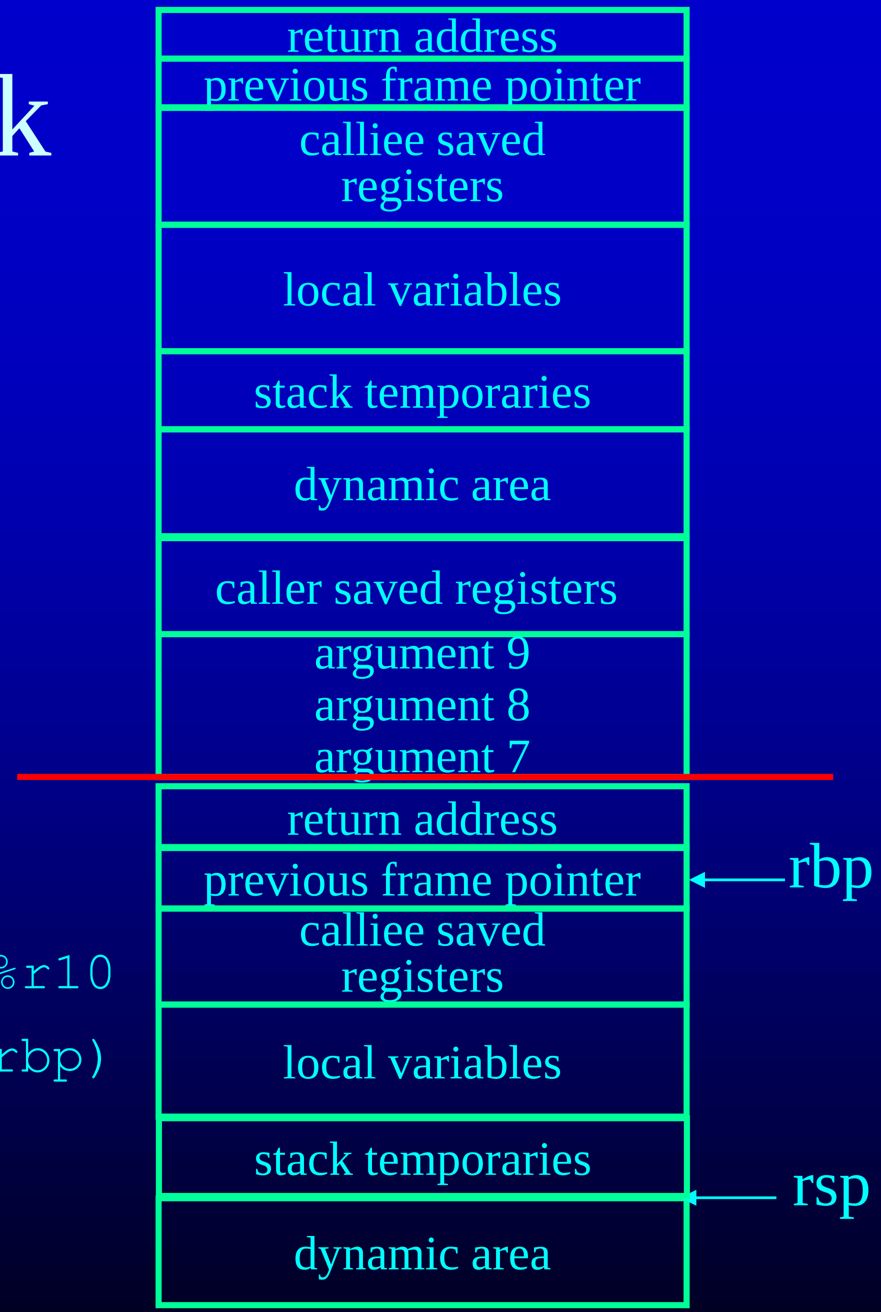
Stack

- Locals and Temporaries
  - Calculate the size and allocate space on the stack

```
    sub          $48, %rsp
or  enter        $48, 0
```

  - Access using -8-xx(%rbp)

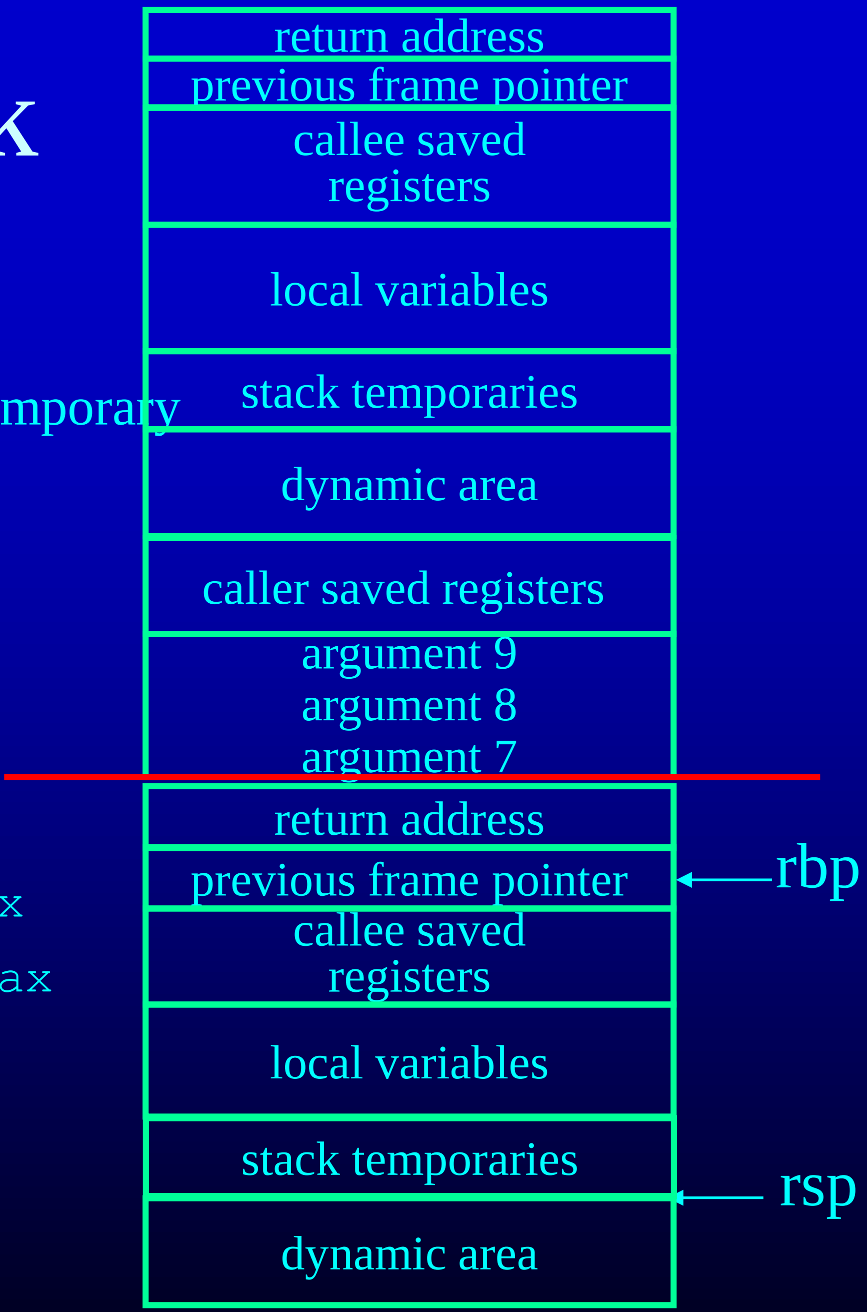
```
    mov          -28(%rbp), %r10
    mov          %r11, -20(%rbp)
```



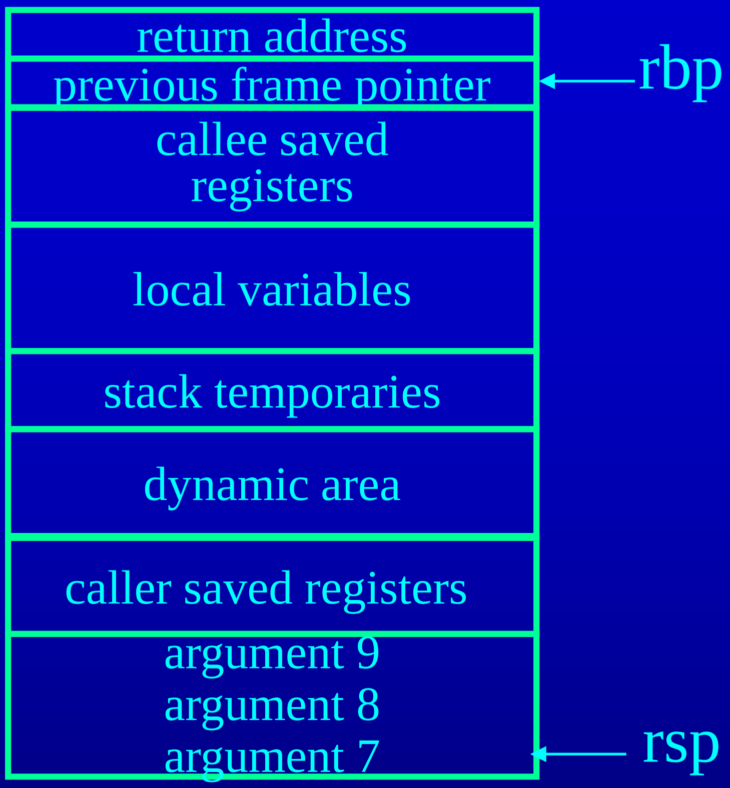
Stack

- Returning Callee
  - Assume the return value is the first temporary
  - Restore the caller saved register
  - Put the return value in %rax
  - Tear-down the call stack

```
mov     -8(%rbp), %rbx
mov     -16(%rbp), %rax
leave
mov     %rbp, %rsp
pop     %rbp
ret
```



Stack



- Returning Caller
- Assume the return value goes to the first temporary
  - Restore the stack to reclaim the argument space
  - Restore the caller save registers
  - Save the return value

```
call    foo
add     $24, %rsp
pop     %rcx
mov     %rax, 8(%rbp)
…
```

Question:

- Do you need the $rbp?
- What are the advantages and disadvantages of having $rbp?

So far we covered..

CODE

- Procedures
- Control Flow
- Statements
- Data Access

DATA

- Global Static Variables
- Global Dynamic Data
- Local Variables
- Temporaries
- Parameter Passing
- Read-only Data

Outline

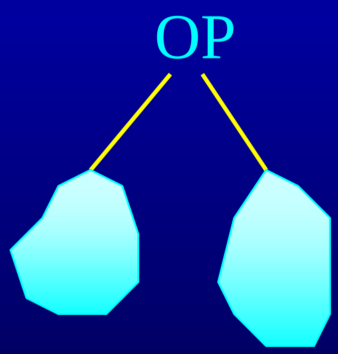
- Generation of expressions and statements
- Generation of control flow
- x86-64 Processor
- Guidelines in writing a code generator

Expressions

- Expressions are represented as trees
  - Expression may produce a value
  - Or, it may set the condition codes (boolean exprs)
- How do you map expression trees to the machines?
  - How to arrange the evaluation order?
  - Where to keep the intermediate values?
- Two approaches
  - Stack Model
  - Flat List Model

Evaluating expression trees

- Stack model
  - Eval left-sub-tree
    Put the results on the stack
  - Eval right-sub-tree
    Put the results on the stack
  - Get top two values from the stack
    perform the operation OP
    put the results on the stack
- Very inefficient!



Evaluating expression trees

- Flat List Model
  - The idea is to linearize the expression tree
  - Left to Right Depth-First Traversal of the expression tree
    - Allocate temporaries for intermediates (all the nodes of the tree)
      - New temporary for each intermediate
      - All the temporaries on the stack (for now)
  - Each expression is a single 3-addr op
    - x = y op z
    - Code generation for the 3-addr expression
      - Load y into register %r10
      - Load z into register %r11
      - Perform `op %r10, %r11`
      - Store %r11 to x

Issues in Lowering Expressions

- Map intermediates to registers?
  - registers are limited
    - when the tree is large, registers may be insufficient ⇒ allocate space in the stack
- No machine instruction is available
  - May need to expand the intermediate operation into multiple machine ops.
- Very inefficient
  - too many copies
  - don't worry, we'll take care of them in the optimization passes
  - keep the code generator very simple

What about statements?

- Assignment statements are simple
  - Generate code for RHS expression
  - Store the resulting value to the LHS address
- But what about conditionals and loops?

Outline

- Generation of statements
- Generation of control flow
- Guidelines in writing a code generator

Two Techniques

- Template Matching
- Short-circuit Conditionals

- Both are based on structural induction
  - Generate a representation for the sub-parts
  - Combine them into a representation for the whole

Template for conditionals

```
if (test)
  true_body
else
  false_body
```

```
          <do the test>
          joper lab_true
          <false_body>
          jmp   lab_end
lab_true:
          <true_body>
lab_end:
```

Example Program

```
if(ax > bx)
        dx = ax - bx;
else
        dx = bx - ax;
```

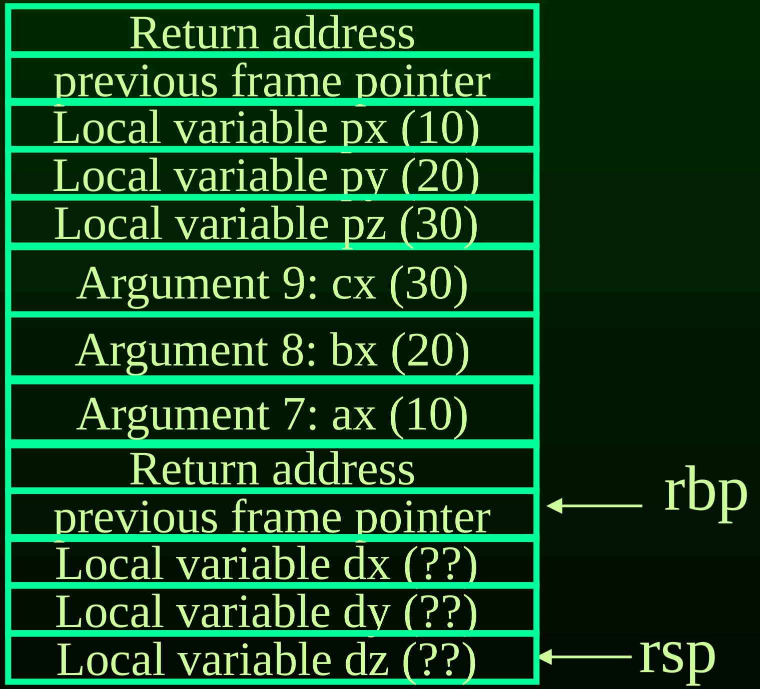
```
        <do test>

        joper  .L0

        <FALSE BODY>

        jmp    .L1
.L0:

        <TRUE BODY>

.L1:
```

Stack	
Return address	
previous frame pointer	
Local variable px (10)	
Local variable py (20)	
Local variable pz (30)	
Argument 9: cx (30)	
Argument 8: bx (20)	
Argument 7: ax (10)	
Return address	
previous frame pointer	← rbp
Local variable dx (??)	
Local variable dy (??)	
Local variable dz (??)	← rsp

Example Program

```
if(ax > bx)
        dx = ax - bx;
else
        dx = bx - ax;
```

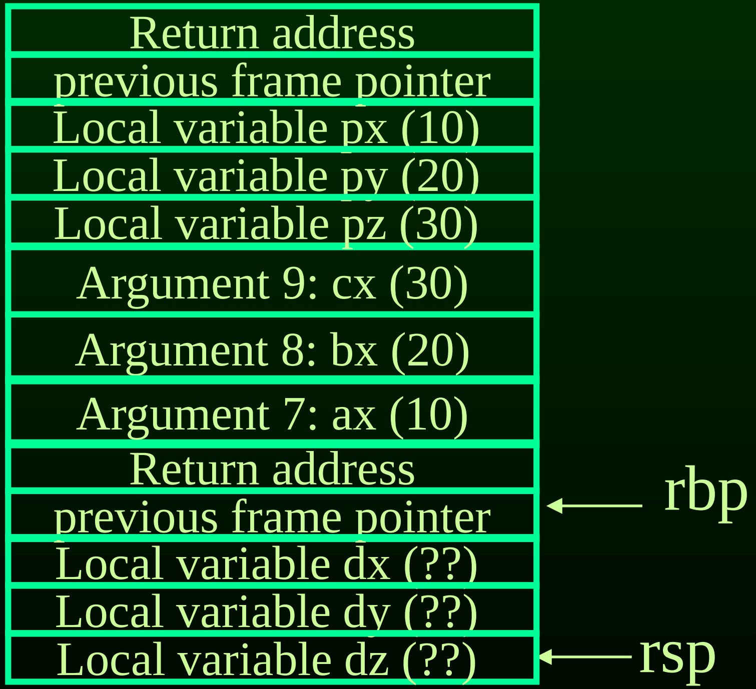
```
        movq    16(%rbp), %r10
        movq    24(%rbp), %r11
        cmpq    %r10, %r11
        jg      .L0

        <FALSE BODY>

        jmp     .L1
.L0:

        <TRUE BODY>

.L1:
```



Example Program

```
if(ax > bx)
        dx = ax - bx;
else
        dx = bx - ax;
```

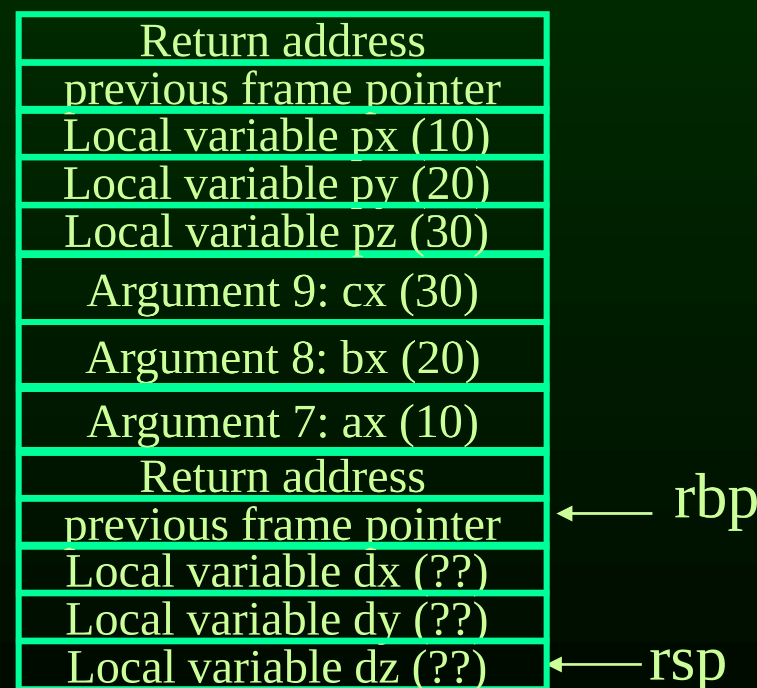
```
        movq    16(%rbp), %r10
        movq    24(%rbp), %r11
        cmpq    %r10, %r11
        jg      .L0
        movq    24(%rbp), %r10
        movq    16(%rbp), %r11
        subq    %r10, %r11
        movq    %r11, -8(%rbp)
        jmp     .L1
.L0:

        <TRUE BODY>

.L1:
```



Example Program

```
if(ax > bx)
        dx = ax - bx;
else
        dx = bx - ax;
```

```
        movq    16(%rbp), %r10
        movq    24(%rbp), %r11
        cmpq    %r10, %r11
        jg      .L0
        movq    24(%rbp), %r10
        movq    16(%rbp), %r11
        subq    %r10, %r11
        movq    %r11, -8(%rbp)
        jmp     .L1
.L0:
        movq    16(%rbp), %r10
        movq    24(%rbp), %r11
        subq    %r10, %r11
        movq    %r11, -8(%rbp)
.L1:
```



Template for while loops

```
while (test)
  body
```

Template for while loops

```
while (test)
  body
```

```
lab_cont:
      <do the test>
      joper lab_body
      jmp   lab_end
lab_body:
      <body>
      jmp   lab_cont
lab_end:
```

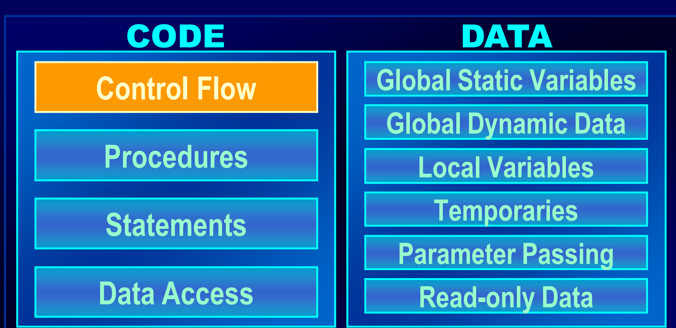
Template for while loops

```
while (test)
  body
```

```
lab_cont:
      <do the test>
      joper lab_body
      jmp   lab_end
lab_body:
      <body>
      jmp   lab_cont
lab_end:
```

- An optimized template

```
lab_cont:
      <do the test>
      joper lab_end
      <body>
      jmp   lab_cont
lab_end:
```



Question:

- What is the template for?

```
do
  body
while (test)
```

Question:

- What is the template for?

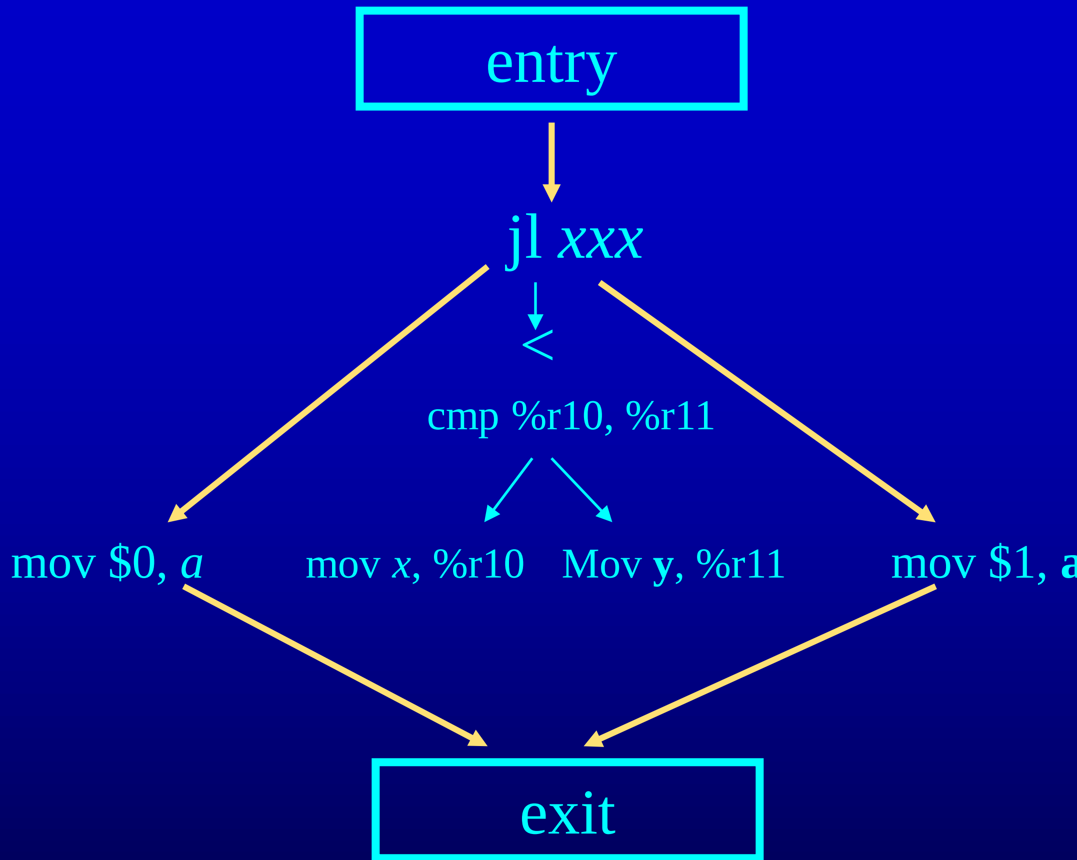
```
do
  body
while (test)
```

```
lab_begin:
      <body>
      <do test>
      joper lab_begin
```

Control Flow Graph (CFG)

- Starting point: high level intermediate format, symbol tables
- Target: CFG
  - CFG Nodes are Instruction Nodes
  - CFG Edges Represent Flow of Control
  - Forks At Conditional Jump Instructions
  - Merges When Flow of Control Can Reach A Point Multiple Ways
  - Entry and Exit Nodes

```
if (x < y) {
        a = 0;
} else {
        a = 1;
}
```



Pattern for if then else

Short-Circuit Conditionals

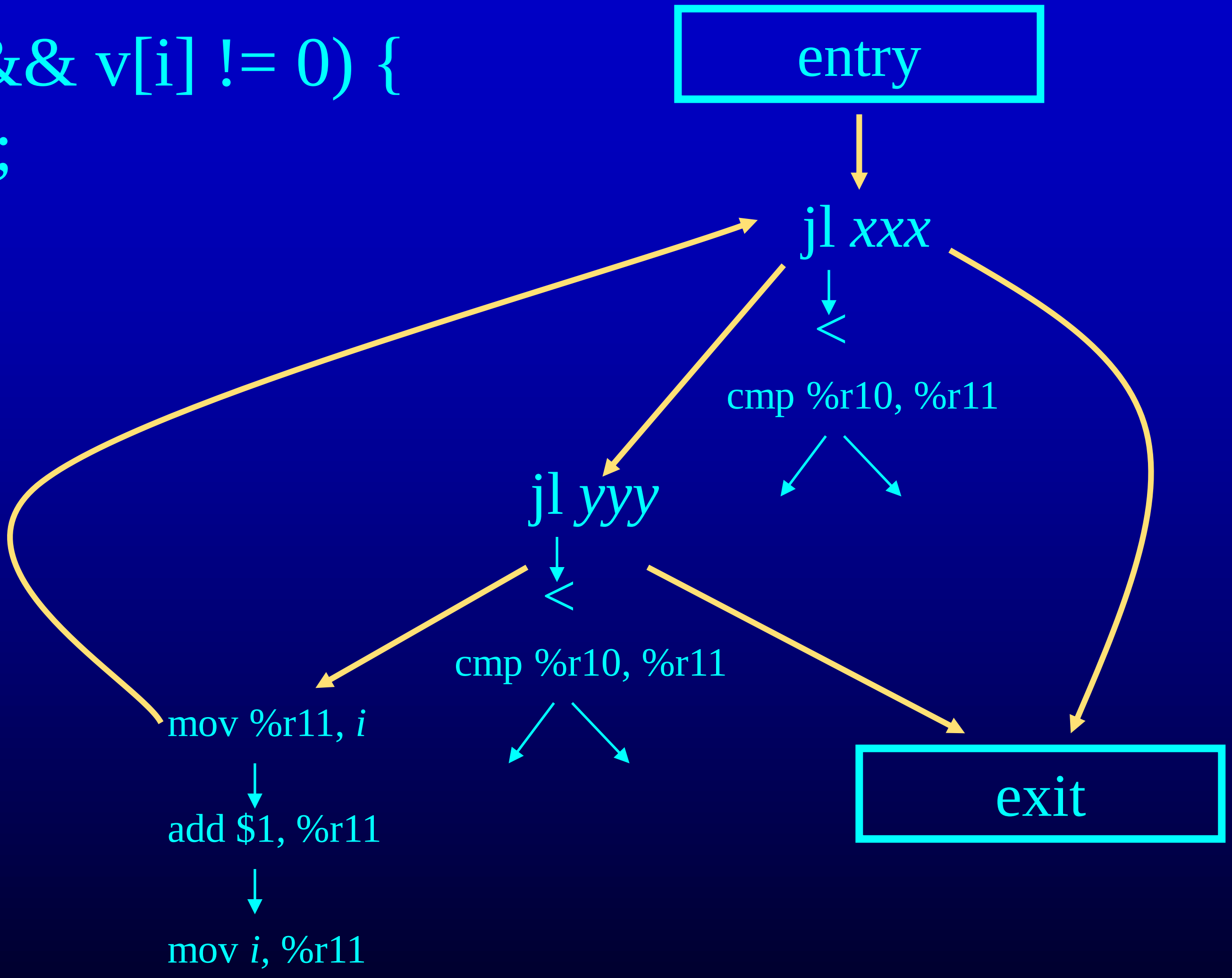
- In program, conditionals have a condition written as a boolean expression

  ((i < n) && (v[i] != 0)) || (i > k)

- Semantics say should execute only as much as required to determine condition
  - Evaluate (v[i] != 0) only if (i < n) is true
  - Evaluate i > k only if ((i < n) && (v[i] != 0)) is false
- Use control-flow graph to represent this short-circuit evaluation

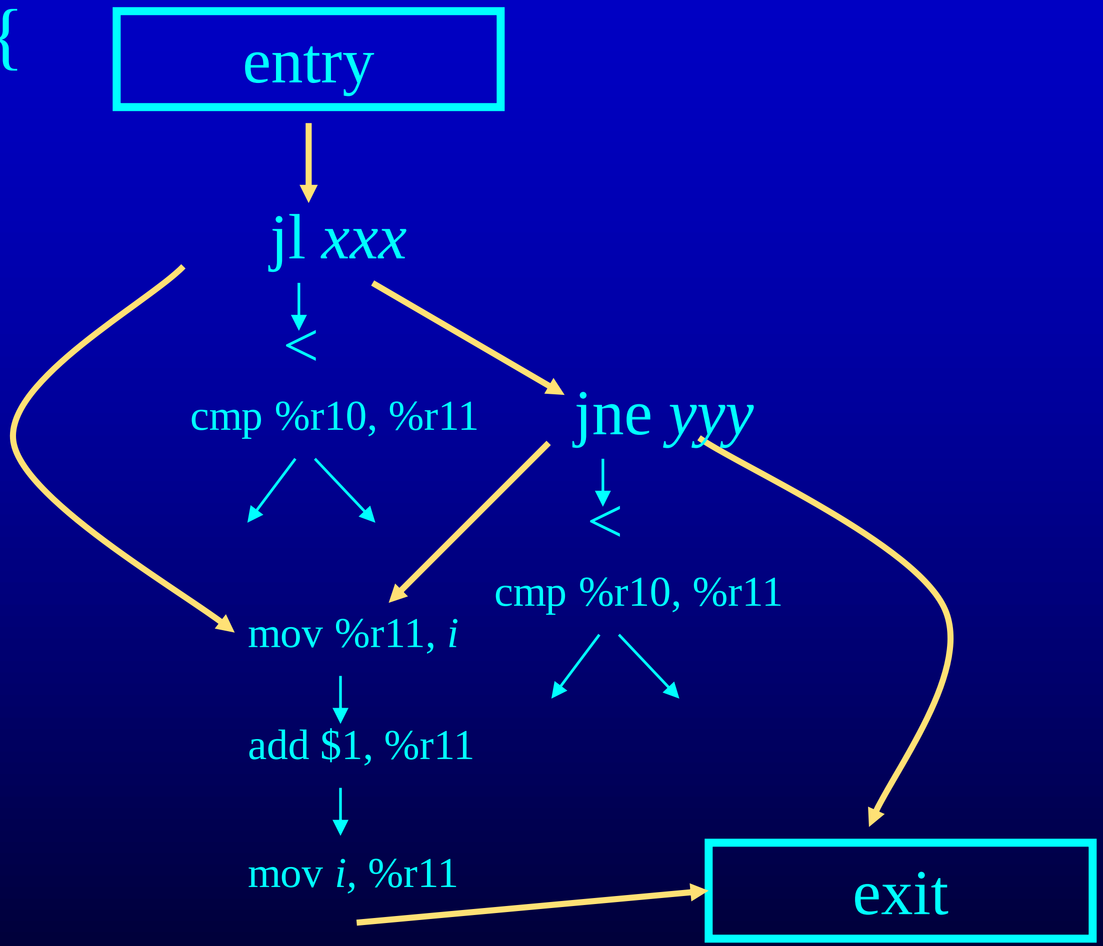
Short-Circuit Conditionals

```
while (i < n && v[i] != 0) {
        i = i+1;
}
```



More Short-Circuit Conditionals

```
if (a < b || c != 0) {
        i = i+1;
}
```



Routines for Destructuring Program Representation

destruct(n)

generates lowered form of structured code represented by n

returns (b,e) - b is begin node, e is end node in destructed form

shortcircuit(c, t, f)

generates short-circuit form of conditional represented by c

if c is true, control flows to t node

if c is false, control flows to f node

returns b - b is begin node for condition evaluation

new kind of node - nop node

Destructuring Seq Nodes

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- generates lowered form of structured code represented by n
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- if n is of the form seq x y

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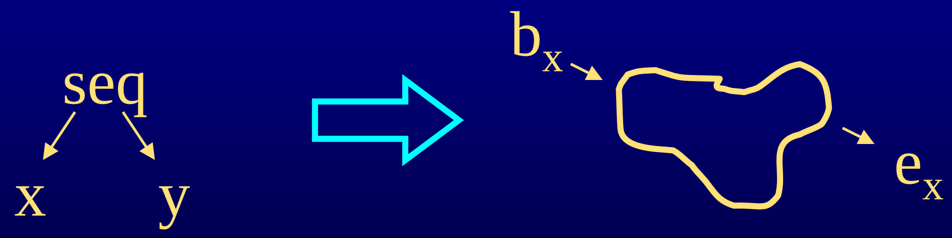
  - 1: (b_x,e_x) = destruct(x);



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- if n is of the form seq x y
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Destructuring Seq Nodes

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- generates lowered form of structured code represented by n
- returns (b,e) - b is begin node, e is end node in destructed form
- if n is of the form seq x y
  - 1: (b_x,e_x) = destruct(x); 2: (b_y,e_y) = destruct(y);
  - 3: $next(e_x) = b_y$;

Destructuring Seq Nodes

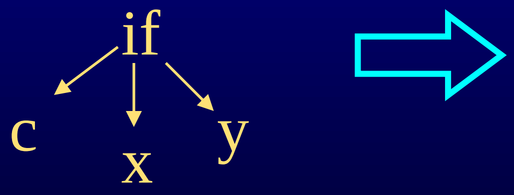
destruct(n)

- generates lowered form of structured code represented by n
- returns (b,e) - b is begin node, e is end node in destructed form
- if n is of the form seq x y
  - 1: (b_x,e_x) = destruct(x); 2: (b_y,e_y) = destruct(y);
  - 3: next$(e_x) = b_y$; 4: return (b_x, e_y);

Destructuring If Nodes

destruct(n)

- generates lowered form of structured code represented by n
- returns (b,e) - b is begin node, e is end node in destructed form
- if n is of the form if c x y



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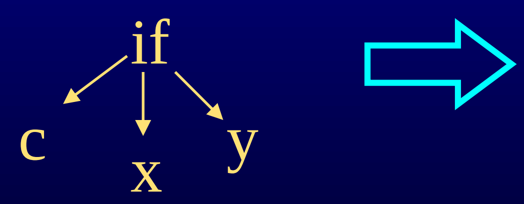

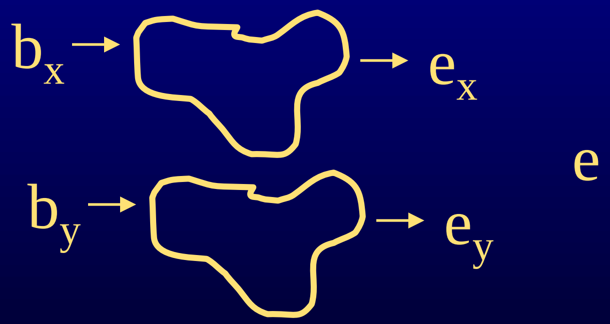

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1: (b_x, e_x) = destruct(x); 2: (b_y, e_y) = destruct(y);

3: e = new nop; 4: next(e_x) = e; 5: next(e_y) = e;

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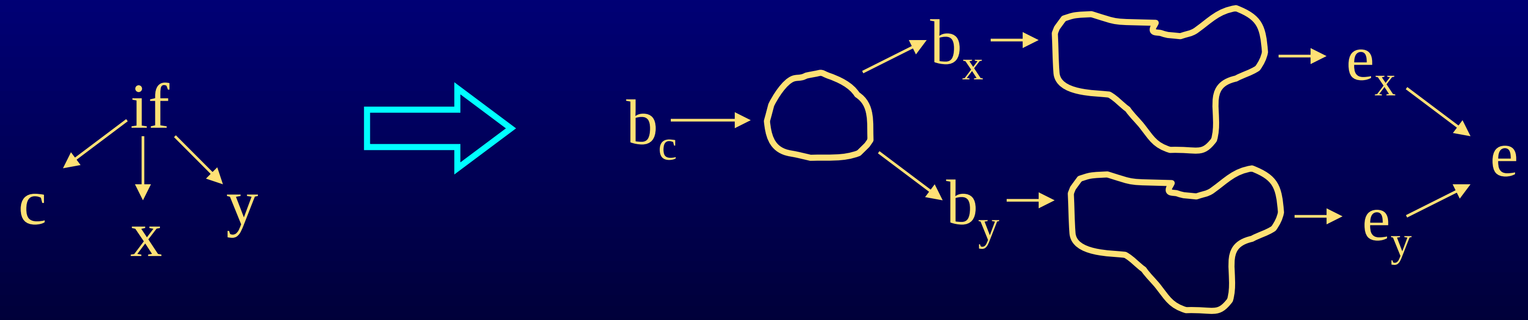
6: b_c = shortcircuit(c, b_x, b_y);



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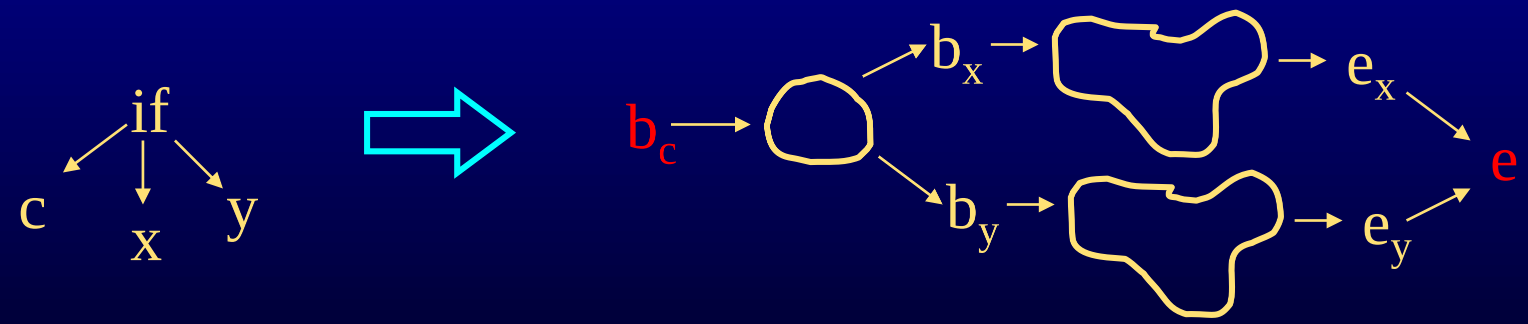
  - 6: b_c = shortcircuit(c, b_x, b_y); 7: return (b_c, e);



Destructuring While Nodes

destruct(n)

generates lowered form of structured code represented by n

returns (b,e) - b is begin node, e is end node in destructed form

if n is of the form while c x

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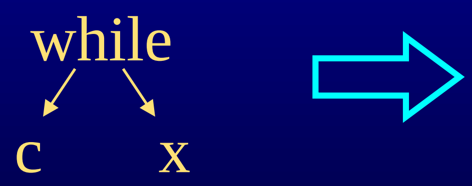

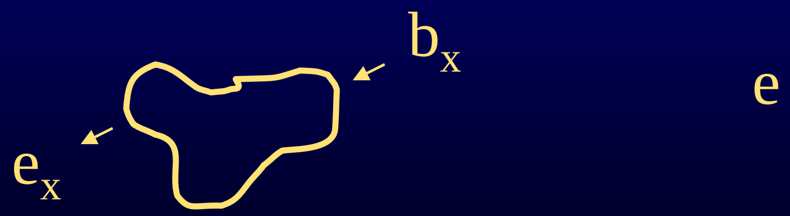

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returns (b,e) - b is begin node, e is end node in destructed form

if n is of the form while c x

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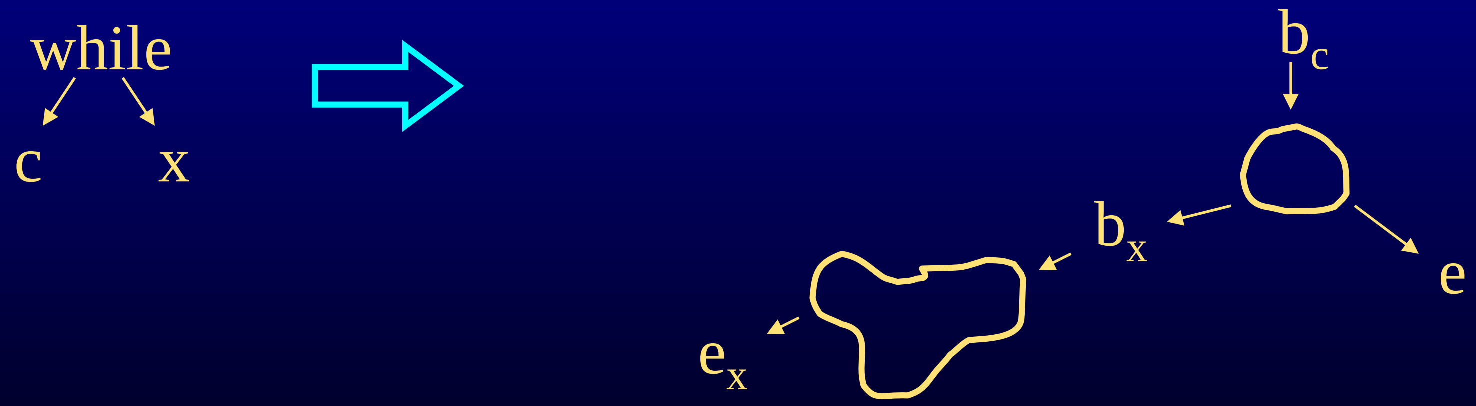
3: b_c = shortcircuit(c, b_x, e);



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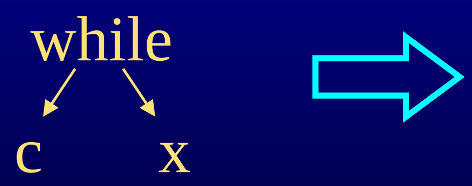

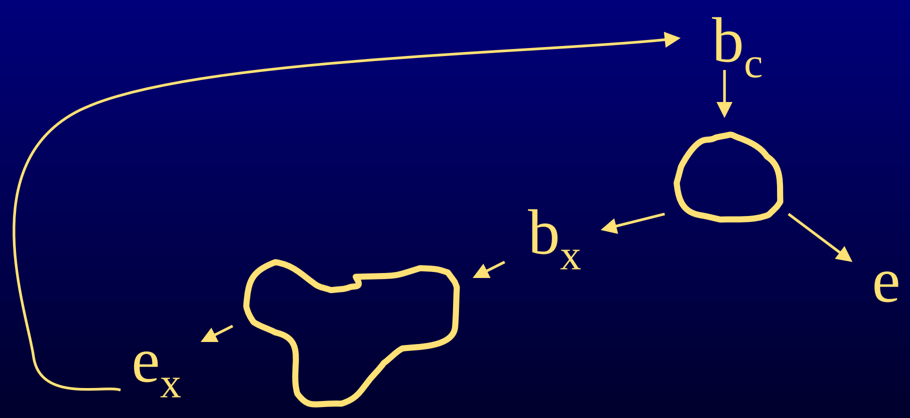

Destructuring While Nodes

destruct(n)

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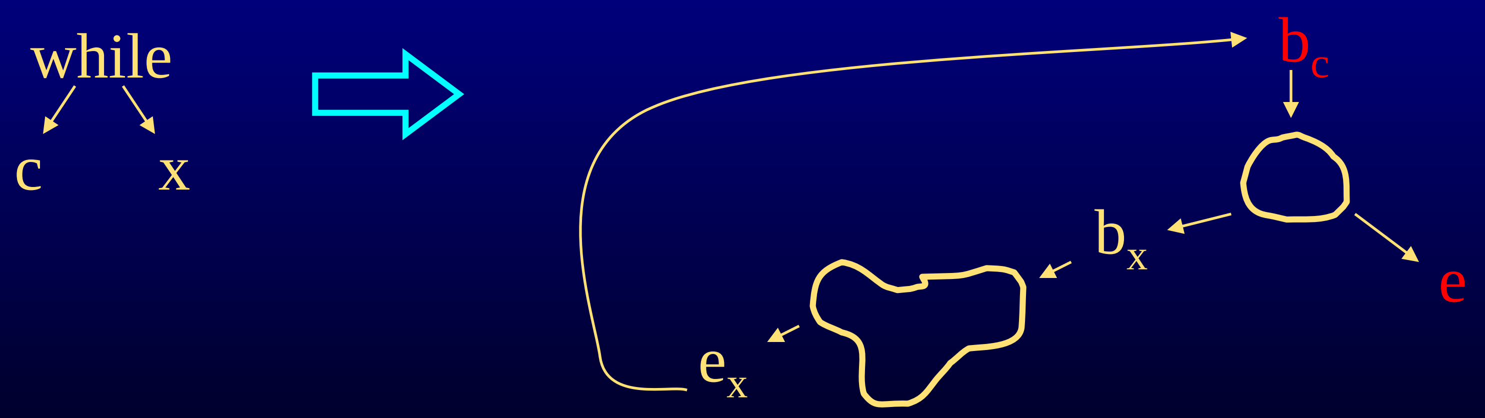
if n is of the form while c x

1: e = new nop; 2: (b_x,e_x) = destruct(x);

3: b_c = shortcircuit(c, b_x, e); 4: next(e_x) = b_c; 5: return (b_c, e);



Shortcircuiting And Conditions

shortcircuit(c, t, f)

- generates shortcircuit form of conditional represented by c
- returns b - b is begin node of shortcircuit form
- if c is of the form c_1 && c_2

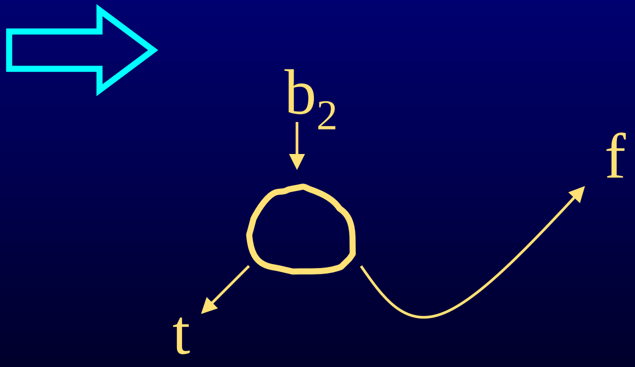
c_1 && c_2

Shortcircuiting And Conditions

shortcircuit(c, t, f)

- generates shortcircuit form of conditional represented by c
- returns b - b is begin node of shortcircuit form
- if c is of the form c_1 && c_2
  - 1: b_2 = shortcircuit(c_2, t, f);

c_1 && c_2



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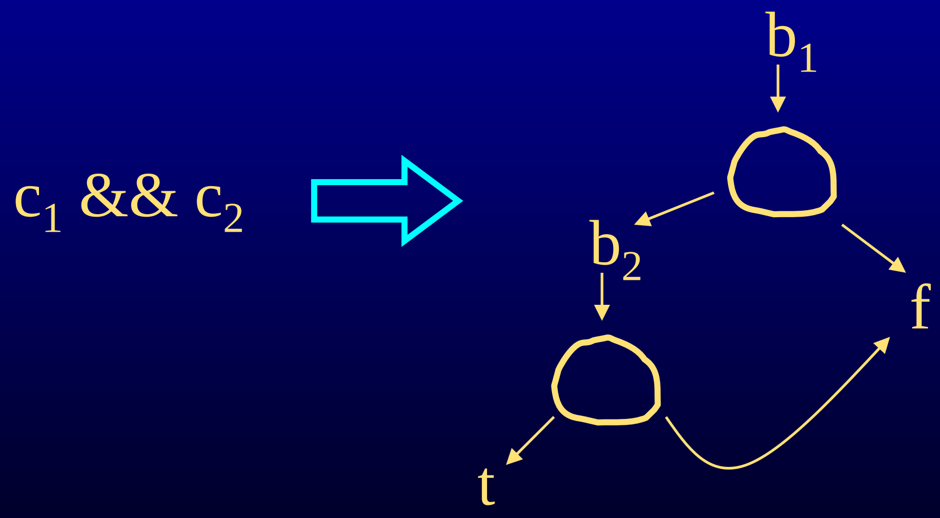
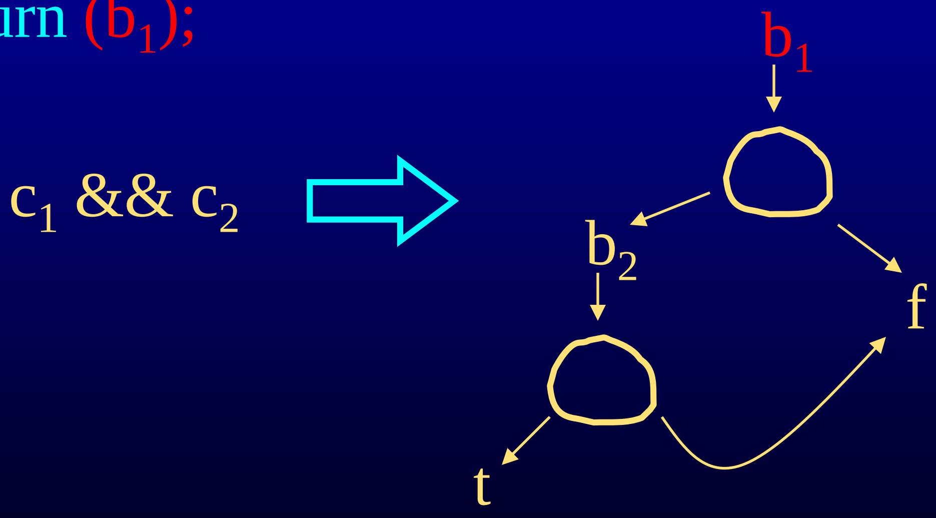
- returns b - b is begin node of shortcircuit form
- if c is of the form c_1 && c_2
  - 1: b_2 = shortcircuit(c_2, t, f); 2: b_1 = shortcircuit(c_1, b_2, f);



Shortcircuiting And Conditions

shortcircuit(c, t, f)

- generates shortcircuit form of conditional represented by c
- returns b - b is begin node of shortcircuit form
- if c is of the form c_1 && c_2
  - 1: b_2 = shortcircuit(c_2, t, f); 2: b_1 = shortcircuit(c_1, b_2, f);
  - 3: return (b_1);



Shortcircuiting Or Conditions

shortcircuit(c, t, f)

generates shortcircuit form of conditional represented by c

returns b - b is begin node of shortcircuit form

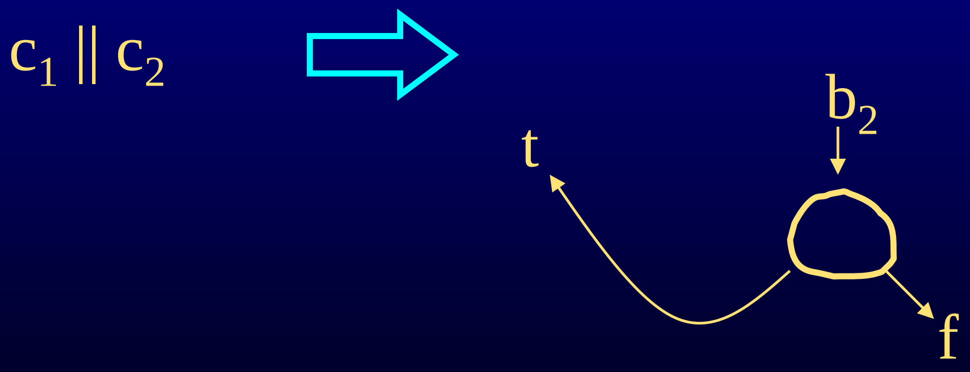
if c is of the form c_1 || c_2

c_1 || c_2

Shortcircuiting Or Conditions

shortcircuit(c, t, f)

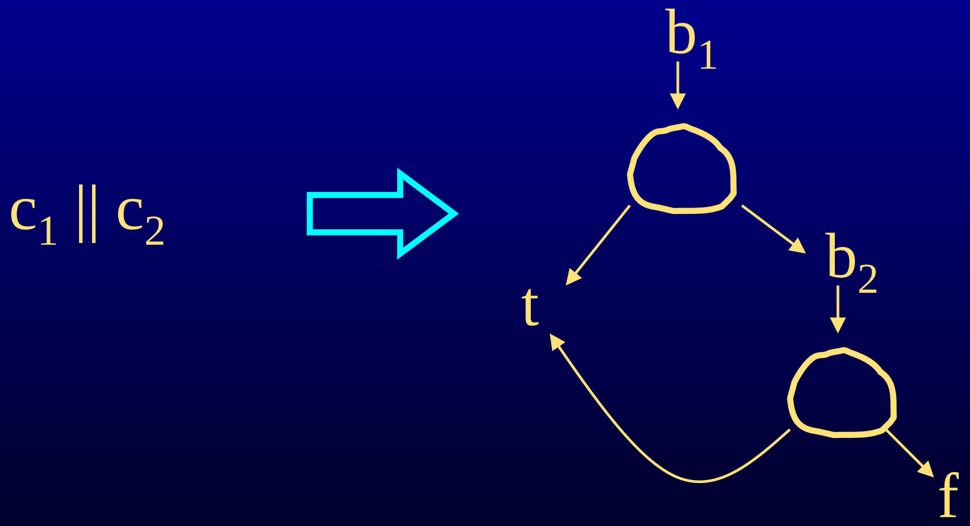
- generates shortcircuit form of conditional represented by c
- returns b - b is begin node of shortcircuit form
- if c is of the form $c_1 \mid\mid c_2$
  - 1: b_2 = shortcircuit(c_2, t, f);



Shortcircuiting Or Conditions

shortcircuit(c, t, f)

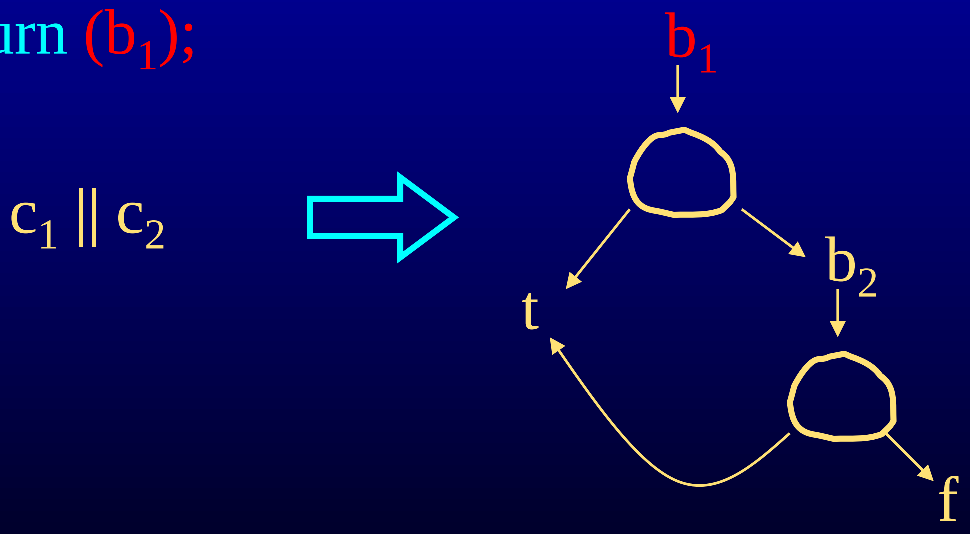
- generates shortcircuit form of conditional represented by c
- returns b - b is begin node of shortcircuit form
- if c is of the form $c_1 \| c_2$
  - 1: b_2 = shortcircuit(c_2, t, f); 2: b_1 = shortcircuit(c_1, t, b_2);



Shortcircuiting Or Conditions

shortcircuit(c, t, f)

- generates shortcircuit form of conditional represented by c
- returns b - b is begin node of shortcircuit form
- if c is of the form $c_1 \parallel c_2$
  - 1: b_2 = shortcircuit(c_2, t, f); 2: b_1 = shortcircuit(c_1, t, b_2);
  - 3: return (b_1);



Shortcircuiting Not Conditions

shortcircuit(c, t, f)

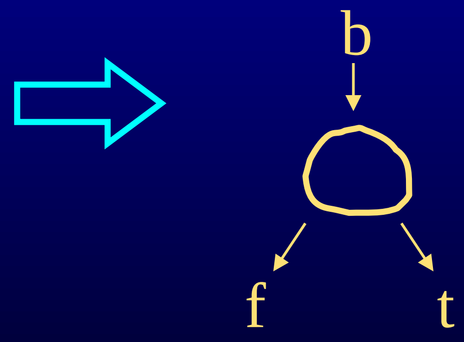
generates shortcircuit form of conditional represented by c

returns b - b is begin node of shortcircuit form

if c is of the form ! c_1

1: b = shortcircuit(c_1, f, t); return(b);

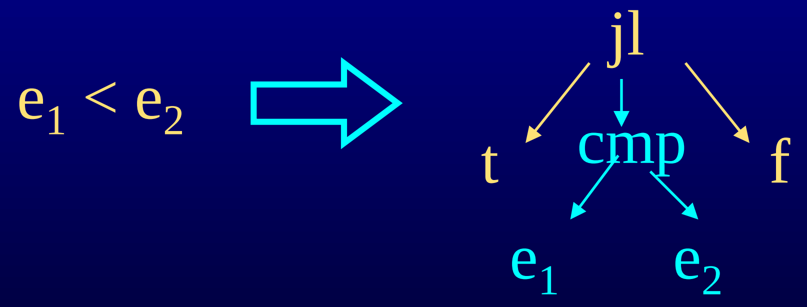
! c_1



Computed Conditions

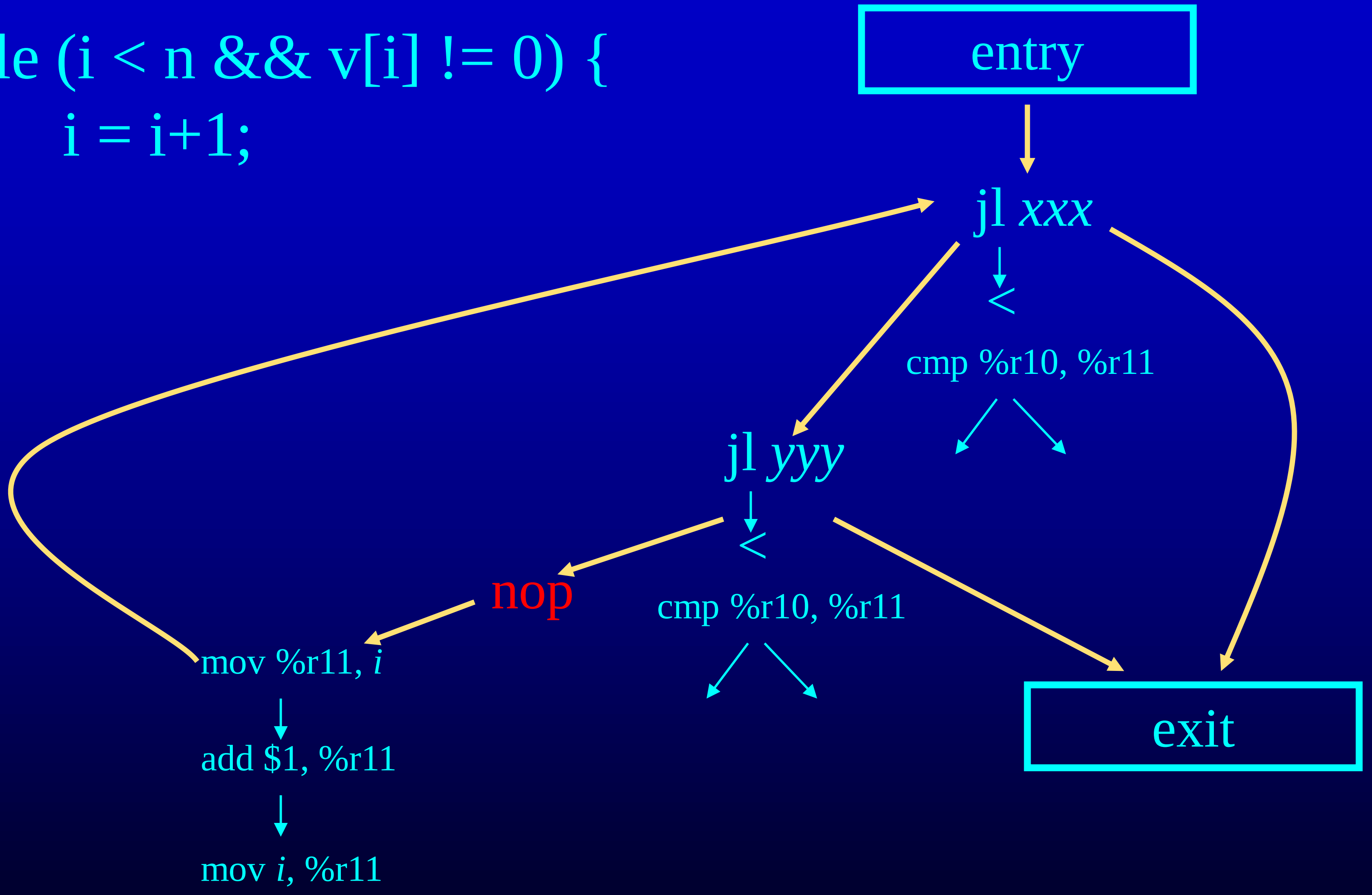
shortcircuit(c, t, f)

- generates shortcircuit form of conditional represented by c
- returns b - b is begin node of shortcircuit form
- if c is of the form $e_1 < e_2$
  - 1: b = new cbr($e_1 < e_2$, t, f); 2: return (b);

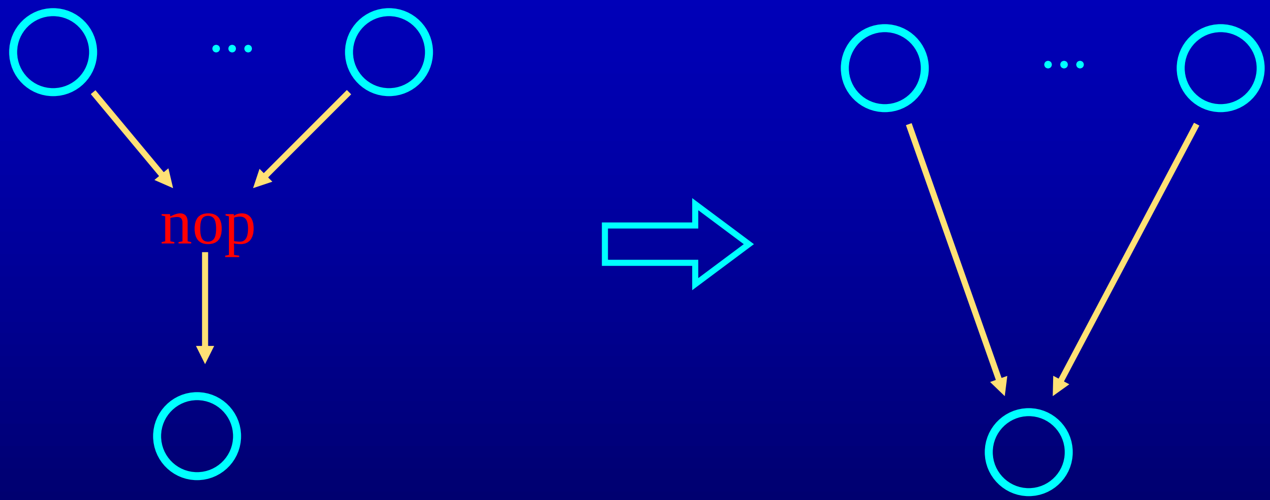


Nops In Destructured Representation

```
while (i < n && v[i] != 0) {
        i = i+1;
}
```



Eliminating Nops Via Peephole Optimization



Linearizing CFG to Assembler

- Generate labels for edge targets at branches
  - Labels will correspond to branch targets
  - Can use patterns for this
- Generate code for statements/conditional expressions
- Generate code for procedure entry/exit

Outline

- Generation of statements
- Generation of control flow
- x86-64 Processor
- Guidelines in writing a code generator

Guidelines for the code generator

- Lower the abstraction level slowly
  - Do many passes, that do few things (or one thing)
  - Easier to break the project down, generate and debug
- Keep the abstraction level consistent
  - IR should have ‘correct’ semantics at all time
  - At least you should know the semantics
  - You may want to run some of the optimizations between the passes.
- Write sanity checks, consistency checks, use often

Guidelines for the code generator

- Do the simplest but dumb thing
  - it is ok to generate 0 + 1*x + 0*y
  - Code is painful to look at; let optimizations improve it

- Make sure you know want can be done at…
  - Compile time in the compiler
  - Runtime using generated code

Guidelines for the code generator

- Remember that optimizations will come later
  - Let the optimizer do the optimizations
  - Think about what optimizer will need and structure your code accordingly
  - Example: Register allocation, algebraic simplification, constant propagation
- Setup a good testing infrastructure
  - regression tests
    - If a input program creates a bug, use it as a regression test
  - Learn good bug hunting procedures
    - Example: binary search , delta debugging