EECS 483: Compiler Construction

Lecture 04:
Conditionals

January 26, 2026

Announcements

- Assignment 1 is due on Friday, the 30th.
- Next assignment to be released on Monday, February 2nd.

Learning Objectives

Syntax and semantics for conditional expressions.

How conditional control flow is encoded in x86

How the instruction pointer is (implicitly) manipulated in x86

How to extend our Basic Block IR to an SSA IR with conditional branching.

How to lower from conditional expressions to SSA IR

Extending the Snake Language

When we implement a compiler (to assembly) we need to address the following questions:

1. What is the syntax of the language we are compiling?
2. What is the semantics of the language we are compiling?
3. How can we implement that semantics in assembly code?
4. How can we generate that assembly code programmatically?

Extending the Snake Language

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4. **How should we adapt our intermediate representation to new features?**
5. How can we generate assembly code from the IR?

Snake v0.2: "Boa"

In Adder we developed straightline code that performed arithmetic operations and stored variables and intermediate results in memory.

In Boa, we extend this to include conditional and looping control flow.

Snake v0.2: "Boa"

⟨*expr*⟩: ...

| `if` ⟨expr⟩ `:` ⟨expr⟩ `else:` ⟨expr⟩

Abstract Syntax

```
enum Exp {
  ...
  If { cond: Box<Exp>, thn: Box<Exp>, els: Box<Exp> }
}
```

Examples, Semantics

We only have one datatype of integers, no separate booleans. We'll use C's convention: 0 is false and everything else is true

Concrete Syntax	Answer
`if 5: 6 else: 7`	6
`if 0: 6 else: 7`	7
`if sub1(1): 6 else: 7`	7

Examples, Semantics

Again we have added if as an **expression** form (like Rust), so we need to handle cases like

```
(if x: 6 else: 8) + (if y: x else: 3)
```

similar to C's ternary operator `x ? 6 : 8`

For this reason, if expressions always have an else branch

Examples, Semantics

We want to ensure that our if expressions only evaluate **one** of the two branches at runtime, and not both.

How would you test that you did this correctly? What kinds of programs would behave differently if you always evaluated both branches?

```
if x:
  print(1)
else:
  print(0)
```

```
let x = 1 in
if x:
  7
else:
  infinite-loop
```

Scope

How should scoping extend to if expressions?

Should the following program be considered well scoped?

```
def main(x):
if 0:
  y
else:
  x
```

Control Flow in x86

Assembly code doesn't have a primitive If construct. How do we express conditional control flow?

x86 Instruction Semantics

So far, instructions execute in sequence. Why?

The instruction to execute is determined by a special register, the **instruction pointer "rip"**.

> in our abstract machine, each execution step starts by interpreting the memory at **[rip]** as a binary encoding of an assembly code instruction.
>
> Most instructions (mov, add, etc) increment rip by the size of the encoded instruction, meaning at the next step the instruction pointer will execute the instruction after it in memory
>
> What instruction have we seen so far that works differently?

x86 Instruction Semantics

So when we look at our code, we should think of it that we are looking at that code laid out in memory.

Assembly code **labels** give names to memory addresses.

```
entry:
  mov rax, rdi
  sub rax, 1
  cmp rax, 0
  je thn
els:
  mov rax, 7
  ret
thn:
  mov rax, 6
  ret
```

x86 Instructions: jmp

```
jmp loc
```

Semantics: sets the instruction pointer to loc.

Often loc is a **label** for another instruction in the same assembly file, but it doesn't have to be, it can be a register, or a memory location, or even a constant (almost certainly will crash in that case)

x86 Instructions: *jcc*

jcc loc

Actually a family of instructions, where **cc** is a **condition code**

Semantics: sets rip to loc **if the condition code is satisfied**, otherwise increment rip like a sequential instruction.

x86 RFLAGS

The x86 abstract machine includes a register **rflags**, which like **rip** is manipulated as a side-effect of many instructions.

rflags is a 64-bit register, each bit acting as a boolean flag. Most of these are irrelevant to our compiler (or unused). The most relevant to us are

- OF "overflow flag": 1 if an overflow occurs, otherwise 0

- SF "sign flag": 1 if the output is negative, otherwise 0

- ZF "zero flag": 1 if the output is zero, otherwise 0

x86 RFLAGS

The x86 abstract machine includes a register **rflags**, which like **rip** is manipulated as a side-effect of many instructions.

mov does not affect flags

add, sub, imul, other arithmetic expressions do:

```
mov rax, 15
mov rcx, 17
sub rax, rcx
```

```
OF: 0
SF: 1
ZF: 0

rax: -2
rcx: 17
```

x86 Instruction: cmp

Often we want to set **rflags**, but not actually store an arithmetic result:

```
cmp arg1, arg2
```

"compare instruction". Behaves like **sub** for the purposes of setting flags, but does **not** update arg1

```
mov rax, 15
mov rcx, 17
cmp rax, rcx
```

```
OF: 0
SF: 1
ZF: 0

rax: 15
rcx: 17
```

x86 Instruction: test

Often we want to set **rflags**, but not actually store an arithmetic result:

```
test arg1, arg2
```

"test instruction". Behaves like a bitwise **and** for the purposes of setting flags, but does **not** update arg1. Useful for checking certain bits are set

x86 Condition codes

Condition codes interpret the flags as a boolean formula. Mnemonic makes the most sense if we have just run a **sub** or **cmp** operation

- e (equal): ZF

- ne (not equal): ~ ZF

- l (less than): OF ^ SF

- le (lesser or equal): (OF ^ SF) | ZF

- g (greater than): ~ le = ~ ((OF ^ SF) | ZF)

- ge (greater or equal): ~ l = ~ (OF ^ SF)

x86 Instructions: *jcc*

```
jcc loc
```

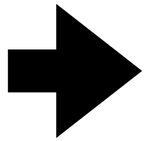
Actually a family of instructions, where **cc** is a **condition code**

Semantics: sets rip to loc **if the condition code is satisfied**, otherwise increment rip like a sequential instruction.

```
je loc

jle loc

jg loc

...
```

x86 Conditional Control Flow: Example

```
def main(x):
  if sub1(x):
    6
  else:
    7
```



```
entry:
  mov rax, rdi
  sub rax, 1
  cmp rax, 0
  jne thn
els:
  mov rax, 7
  ret
thn:
  mov rax, 6
  ret
```

Extending the Snake Language

When we implement a compiler (to assembly) we need to address the following questions:

1. What is the syntax of the language we are compiling?
2. What is the semantics of the language we are compiling?
3. How can we implement that semantics in assembly code?
4. **How should we adapt our intermediate representation to new features?**
5. How can we generate assembly code from the IR?

SSA

Previously:

- one single block of operations ending in a return
- compiled to a block of sequential assembly labeled entry, ending in a ret

Extend as follows:

- add ability to define additional labeled blocks called **basic blocks**
- add ability to end a block by **branching** rather than returning

SSA Abstract Syntax

```
pub enum BlockBody {
    Terminator(Terminator),
    Operation {
        dest: VarName,
        op: Operation,
        next: Box<BlockBody>,
    },
    SubBlock {
        block: BasicBlock,
        next: Box<BlockBody>,
    },
}
```

```
pub struct BasicBlock {
    pub label: Label,
    pub body: BlockBody,
}
```

```
pub enum Terminator {
    Return(Immediate),
    ConditionalBranch {
        cond: Immediate,
        thn: Label,
        els: Label,
    },
}
```

SSA Concrete Syntax

```
entry(x):
  thn:
    ret 6
  els:
    ret 7
  sub1_arg = x
  cond = sub sub1_arg 1
  cbr cond thn els
```

Compiling Basic Blocks to x86

For each basic block, we will emit a block of assembly code with a label corresponding to the name of the block.

Need to ensure that the sub-blocks are emitted after the instructions for the current block.

Conditional branches can be encoded using a mix of x86 conditional jumps and unconditional jumps

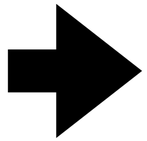
Compiling Basic Blocks to x86

```
entry(x):
  thn:
    ret 6
  els:
    ret 7
  sub1_arg = x
  cond = sub sub1_arg 1
  cbr cond thn els
```

```
entry:
        mov [rsp + -8], rdi
        mov rax, [rsp + -8]
        mov [rsp + -16], rax
        mov rax, [rsp + -16]
        mov r10, 1
        sub rax, r10
        mov [rsp + -24], rax
        mov rax, [rsp + -24]
        cmp rax, 0
        jne thn#0
        jmp els#1
thn#0:
        mov rax, 6
        ret
els#1:
        mov rax, 7
        ret
```

Compiling Conditionals to (Sub-)blocks

```
def main(x):
  if sub1(x):
    6
  else:
    7
```



```
entry(x):
  thn:
    ret 6
  els:
    ret 7
  sub1_arg = x
  cond = sub sub1_arg 1
  cbr cond thn els
```

Conditionals and Continuations

```
enum Exp {
  ...
  If { cond: Box<Exp>, thn: Box<Exp>, els: Box<Exp> }
}
```

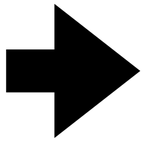
Strategy:

Make basic blocks for thn and els, giving them unique label names, compiling them recursively

Compile cond, do a conditional branch on the result, using the label names generated for thn and els

Compiling Conditionals to (Sub-)blocks

```
if cond:
  thn
else:
  els
```



```
thn%uid:
  ... thn code
els%uid':
  ... els code
... cond code
cond_result%uid'' = ...
cbr cond_result%uid'' thn%uid els%uid'
```

Conditionals and Continuations

This works if the result of the if expression is to be returned, but what if it's more complex:

```
let x = (if y: 5 else: 6) in
x * 3
```

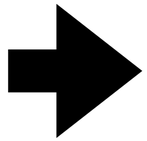
We need to also account for the **continuation** of the if expression!

The continuation is what should happen **after** the result of the expression is computed. Now that result might be computed in either branch.

So the continuation needs to be run after either branch

Compiling Conditionals by Copying Continuations

```
if cond:
  thn
else:
  els
```



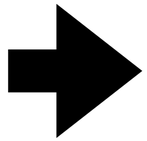
```
thn%uid:
  ... thn code
els%uid':
  ... els code
... cond code
cond_result%uid'' = ...
cbr cond_result%uid'' thn%uid els%uid'
```

Compiling Conditionals by Copying Continuations

```
if cond:
  thn
else:
  els
```

+

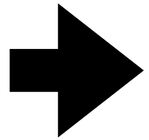
```
... continuation code
```



```
thn%uid:
  ... thn code
  ... continuation code
els%uid':
  ... els code
  ... continuation code
... cond code
cond_result%uid'' = ...
cbr cond_result%uid'' thn%uid els%uid'
```

Compiling Conditionals by Copying Continuations

```
let x = (if y: 5 else: 6) in
x * 3
```



```
thn%0:
  x%2 = 5
  res%3 = x%2 * 3
  ret res%3
els%1:
  x%4 = 6
  res%3 = x%4 * 3
  ret res%3
cbr y%5 thn%0 els%1
```

Compiling Conditionals by Copying Continuations

Strategy:

- Make basic blocks for thn and els, giving them unique label names, compiling them recursively
- Compile cond, do a conditional branch on the result, using the label names generated for thn and els
- For continuations: copy them into both branches

But there's a problem!?

- The strategy we've described today does create "correct" code.
- Why is the strategy completely infeasible in practice?

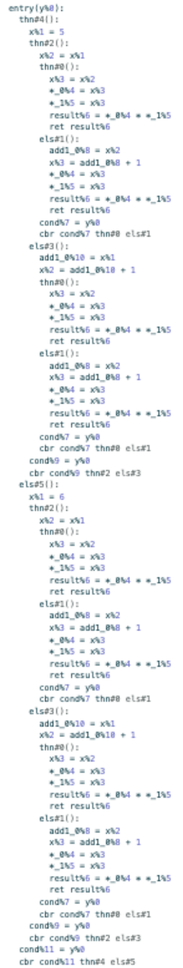
Exponential Blowup in Copying Continuations

```
def main(y):
  let x = if y: 5 else: 6 in
  let x = if y: x else: add1(x) in
  let x = if y: x else: add1(x) in
  x * x
```

If we copy the continuation each time we perform an if, how many times does the

x * x

code appear in the generated ssa program?



Compiling Conditionals by Copying Continuations

Why is the strategy completely infeasible in practice?

Copying continuation: code size is exponential in the number of sequenced if-expressions

Generated code should be usually be linear in the size of the input program

Most compiler passes should be linear in the size of the input program

certain program analyses are not linear, and dominate compilation time

Not Copying Continuations

```
def main(y):
  let x = if y: 5 else: 6 in
  let x = if y: x else: add1(x) in
  let x = if y: x else: add1(x) in
  x * x
```

Copying the continuation is infeasible because it causes an exponential blowup in code size.

But it **does** produce functionally correct code because it correctly identifies that the two branches share the same continuation. The best we can do with our version of SSA.

Need to add something to SSA to allow us to express that two pieces of code share the same continuation.

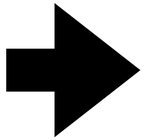
Join Points

How would we write this manually in assembly code without copying?

Make a new block and jump to that same block at the end of each of the branches. This "shares" the continuation without copying, using the fact that we can copy the **reference** to the code, its label, for cheap.

Join Points

```
def main(y):
  let x = (if y: 5 else: 6) in
  x * x
```



```
entry:
        cmp rdi, 0
        jne thn#0
        jmp els#1
thn#0:
        mov rax, 5
        jmp jn#2
els#1:
        mov rax, 6
        jmp jn#2
jn#2:
        imul rax, rax
        ret
```

Join Points

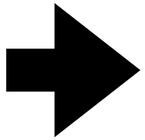
How can we extend our IR to express join points?

Join points are just a new kind of block?

- Make a block for the join point
- Add a new **uncdonditional** branch, like an assembly **jmp** to our IR.

Join Points

```
def main(y):
  let x = (if y: 5 else: 6) in
  x * x
```



```
entry(y%0):
  jn#2:
    ...?
    result%4 = x%1 * x%1
    ret result%4
  thn#0:
    thn_res%6 = 5
    ...?
    br jn#2
  els#1:
    els_res%7 = 6
    ...?
    br jn#2
  cond%5 = y%0
  cbr cond%5 thn#0 els#1
```

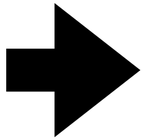
Our ordinary blocks aren't enough: Join points aren't just code blocks, they are **continuations.** We don't just need to execute

x * x

We also need to **assign to x** differently depending on the branch

Solution 1: Assign to x in both branches

```
def main(y):
  let x = (if y: 5 else: 6) in
  x * x
```



```
entry(y%0):
  jn#2:
    result%4 = x%1 * x%1
    ret result%4
  thn#0:
    x%1 = 5
    br jn#2
  els#1:
    x%1 = 6
    br jn#2
  cond%5 = y%0
  cbr cond%5 thn#0 els#1
```

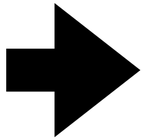
Pros: easy to generate assembly code

Con: breaks the "static single assignment property"

It's not clear in the join point where x is defined, makes program analysis, optimization much harder

Solution 2: ϕ nodes

```
def main(y):
  let x = (if y: 5 else: 6) in
  x * x
```



```
entry(y%0):
  jn#2:
    x%1 = ϕ(thn_res%6, els_res%7)
    result%4 = x%1 * x%1
    ret result%4
  thn#0:
    thn_res%6 = 5
    br jn#2
  els#1:
    els_res%7 = 6
    br jn#2
  cond%5 = y%0
  cbr cond%5 thn#0 els#1
```

Solution 2: ϕ nodes

A ϕ node is a "ϕony" operation that allows SSA format to express join points without breaking the SSA property.

```
x = ϕ(x1,x2,x3,...)
```

The semantics is a little strange...The ϕ node is an assignment to x, but which variable it assigns depends on where we **just** branched **from**.

ϕ nodes require some syntactic restrictions:

- they can only appear at the beginning of a basic block (so that we just branched).
- need to make sure that the variables on the rhs are actually defined before they reach the ϕ node.
- need to pick some kind of ordering, so we actually know which variable corresponds to which branch

Solution 2: ϕ nodes

A ϕ node is a "ϕony" operation that allows SSA format to express join points without breaking the SSA property.

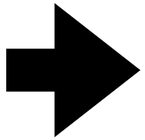
```
x = ϕ(x1,x2,x3,...)
```

Pros: maintains the SSA property, popular in SSA literature, used in long-established industrial SSA-based compilers (LLVM, GCC, Hotspot)

Cons: strange semantics, strange code generation (the move happens in the predecessor block!), difficult to enforce syntactic restrictions

Solution 3: Parameterized Blocks

```
def main(y):
  let x = (if y: 5 else: 6) in
  x * x
```



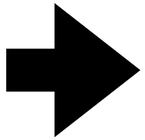
```
entry(y%0):
  jn#2(x%1):
    result%4 = x%1 * x%1
    ret result%4
  thn#0():
    br jn#2(5)
  els#1():
    br jn#2(6)
  cond%5 = y%0
  cbr cond%5 thn#0() els#1()
```

Represent the **continuation** directly in the syntax: a block can have **parameters** just like a continuation has an input variable.

Directly allow us to turn continuations into blocks

Solution 3: Parameterized Blocks

```
def main(y):
  let x = (if y: 5 else: 6) in
  x * x
```



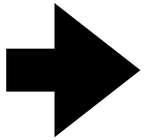
```
entry(y%0):
  jn#2(x%1):
    result%4 = x%1 * x%1
    ret result%4
  thn#0():
    br jn#2(5)
  els#1():
    br jn#2(6)
  cond%5 = y%0
  cbr cond%5 thn#0() els#1()
```

Represent the **continuation** directly in the syntax: a block can have **parameters** just like a continuation has an input variable.

Directly allow us to turn continuations into blocks

Solution 3: Parameterized Blocks

```
def main(y):
  let x = (if y: 5 else: 6) in
  x * x
```



```
entry(y%0):
  jn#2(x%1):
    result%4 = x%1 * x%1
    ret result%4
  thn#0():
    br jn#2(5)
  els#1():
    br jn#2(6)
  cond%5 = y%0
  cbr cond%5 thn#0() els#1()
```

Represent the **continuation** directly in the syntax: a block can have **parameters** just like a continuation has an input variable.

Directly allow us to turn continuations into blocks

ϕ Nodes vs Parameterized Blocks

A parameterized block adds "arguments" to our basic blocks

```
l(x1,x2,x3):
```

These arguments are like other variables, they are in scope for the block, but not outside of it.

Branching to a parameterized block means providing arguments to it

```
br l(y1,y2,y3)
```

Pros: maintains the SSA property, simple code generation, simple well-formedness condition, used in newer SSA-based compilers (Swift, MLIR, MLton)

Cons: separates the different join points syntactically in the SSA program, need to translate most SSA papers from phi node notation

ϕ Nodes vs Parameterized Blocks

```
entry(y%0):
  jn#2:
    x%1 = ϕ(thn_res%6, els_res%7)
    result%4 = x%1 * x%1
    ret result%4
  thn#0:
    thn_res%6 = 5
    br jn#2
  els#1:
    els_res%7 = 6
    br jn#2
  cond%5 = y%0
  cbr cond%5 thn#0 els#1
```

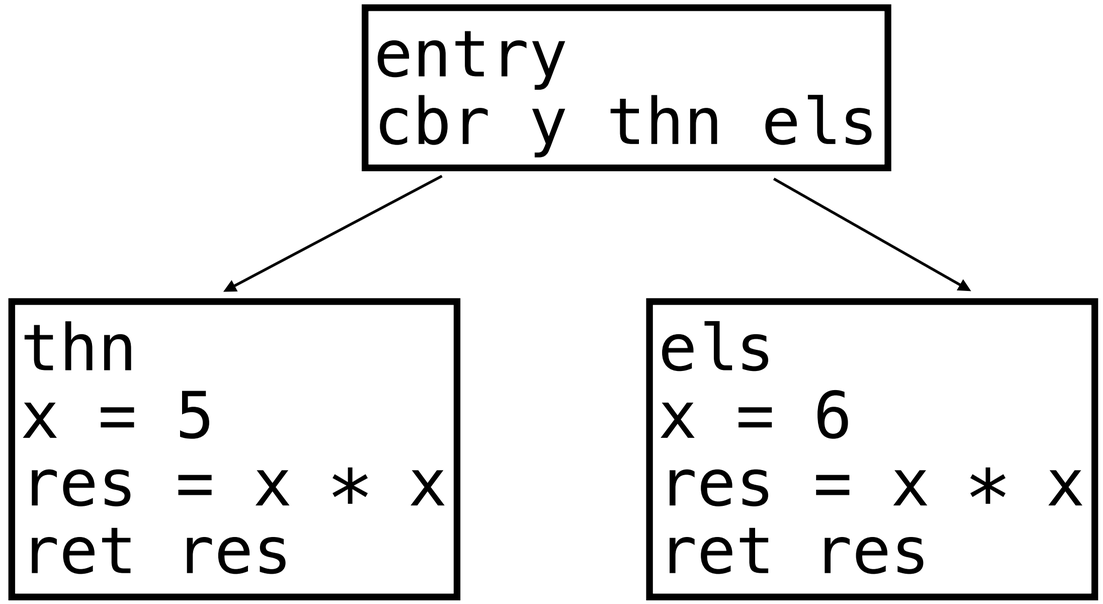
```
entry(y%0):
  jn#2(x%1):
    result%4 = x%1 * x%1
    ret result%4
  thn#0():
    br jn#2(5)
  els#1():
    br jn#2(6)
  cond%5 = y%0
  cbr cond%5 thn#0() els#1()
```

ϕ nodes put assignment in the block itself, parameterized blocks put the "asignment in the predecessor

Control Flow Graph

We can visualize SSA programs using **control-flow graphs**.

```
entry(y%5):
  thn%0:
    x%2 = 5
    res%3 = x%2 * x%2
    ret res%3
  els%1:
    x%4 = 6
    res%3 = x%4 * x%4
    ret res%3
  cbr y%5 thn%0 els%1
```



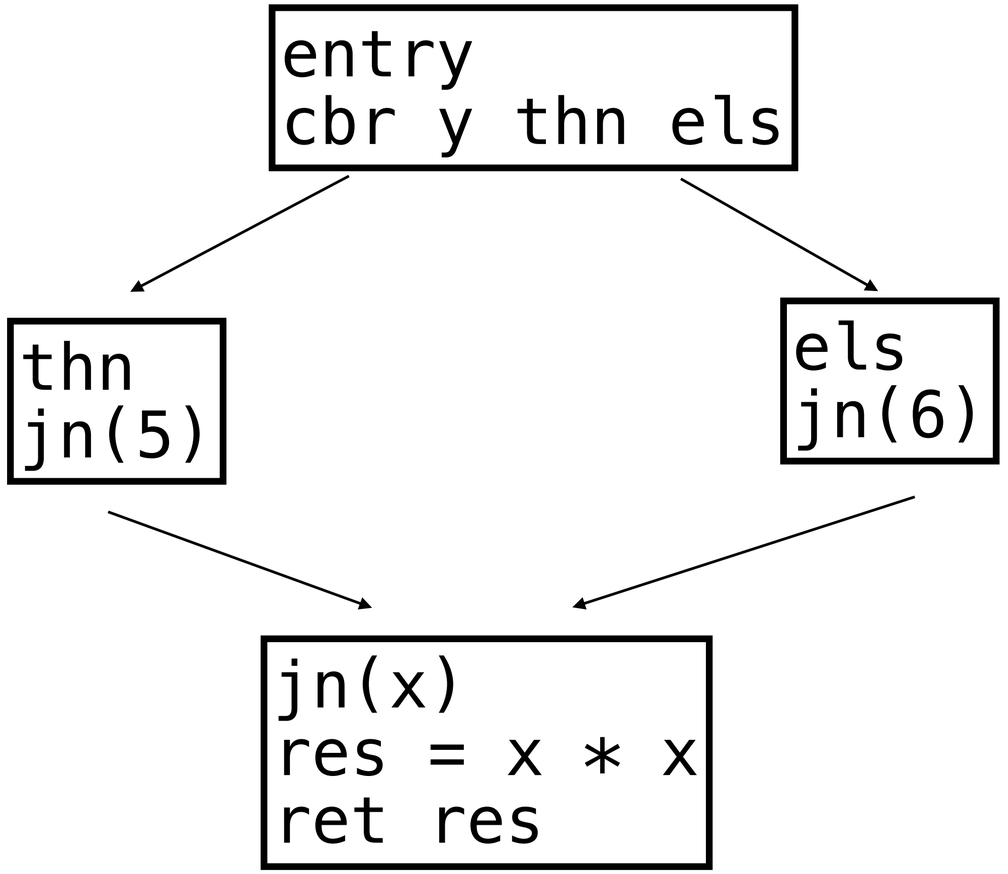
Nodes of CFG: basic blocks
edges are branches

Control Flow Graph

We can visualize SSA programs using **control-flow graphs**.

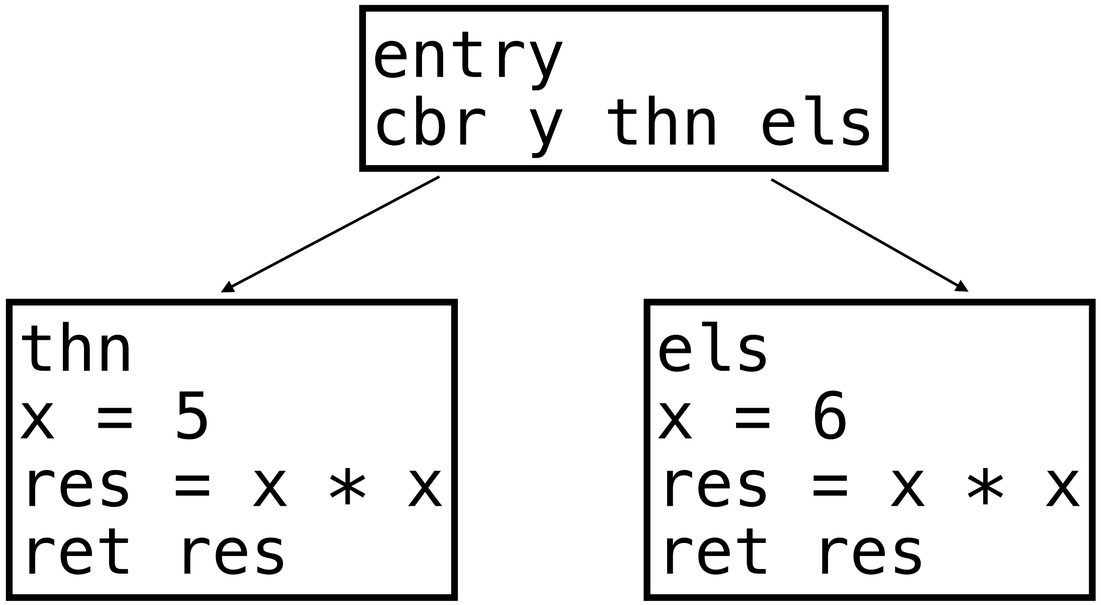
Join point: multiple predecessors

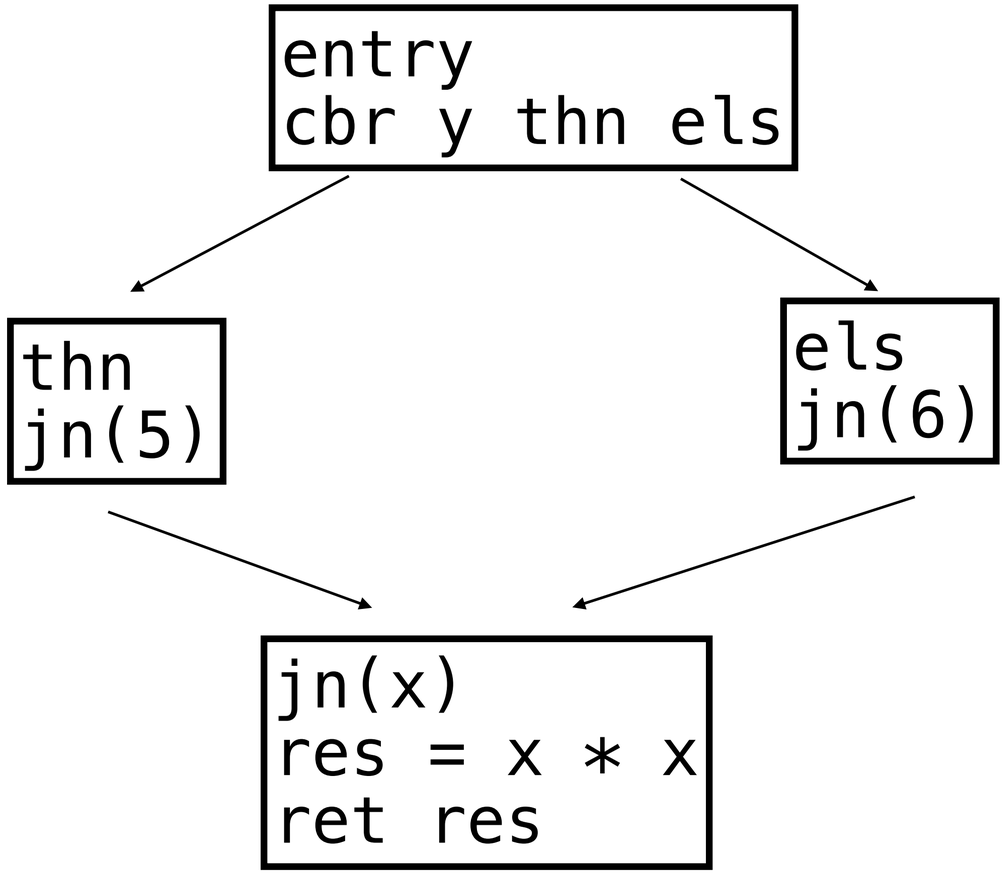
```
entry(y%0):
  jn#2(x%1):
    result%4 = x%1 * x%1
    ret result%4
  thn#0():
    br jn#2(5)
  els#1():
    br jn#2(6)
  cond%5 = y%0
  cbr cond%5 thn#0() els#1()
```



Control Flow Graph

Join points are needed to express **sharing**. Conditional code like our source produces a DAG. DAGs can be simulated with trees, but with an exponential blowup!





Control Flow Graph

A common way to think about SSA programs is in terms of **control-flow graphs**.

With branching, but no join points, we can express control-flow **trees**.

Join points allow us to express control-flow **DAGs** which can be exponentially more compact than trees**.**

If we remove the acyclicity requirement, we can express **loops** and even more exotic control flow. Revisit this next week