# CSC2/455 Software Analysis and Improvement
# Intermediate Representations (IRs)

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URCS

# Outline

Introduction

Midend

Miscellaneous

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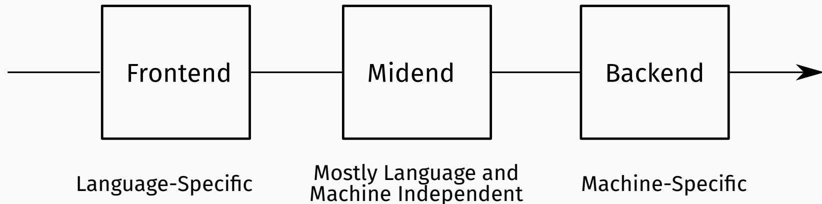
# Classic Compiler Architecture




Recommended reading: Chris Lattner, LLVM, The Architecture of Open Source Applications

# Outline

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# What does the midend do?

- Mostly language and machine independent analyses
- Majority of analyses run in this stage
- Multiple *intermediate representations* used
  - Starts from abstract syntax tree
  - Usually stops before instruction scheduling/register allocation
  - Examples: AST, CFG, DDG, PDG, etc.
- There is no *one* Intermediate Representation (IR)
  - although people have tried ...

# Mid-end structure

- Organized as a set of *passes*
- Each pass usually performs one task
    - Some specific analysis of the IR
    - Some transformation of the IR
- Input to each pass is the IR and output is also the IR
    - And usually analysis results, etc.

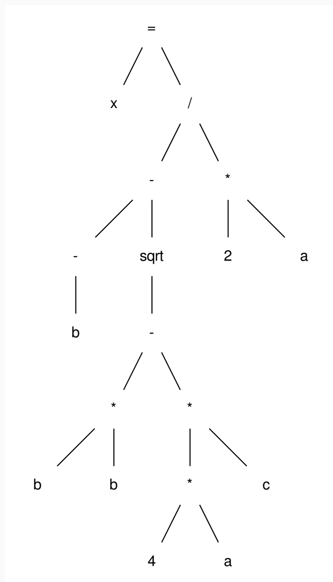
# Running example

$$x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

In Python (assume `math.sqrt` is `sqrt`):

```
x = (-b - sqrt(b*b - 4 * a * c)) / (2*a)
```

# Abstract Syntax Tree



# AST as a list

```
ast = ['=',
       ['x',
        ['/',
         ['-',
          ['neg', 'b'],
          ['sqrt',
           ['-',
            ['*', 'b', 'b'],
            ['*',
             ['*', '4', 'a'],
             'c'
            ]
           ]
          ]
         ],
         ['*', '2', 'a']
        ]
       ]
      ]
```

- What does this remind you of?

## Slightly less LISPy

```
class Node(object):
    operator = None
    left = None
    right = None
```

- Actual ASTs are not binary trees!
  - Will usually have list of `descendants` instead of `left` and `right`
  - `descendants` may be more specific, `while` may have `condition` and `body`

# Linear Forms

- ASTs imply treewalking
  - Works best when manipulating source code
  - e.g. Source-to-source compilers
  - Or when control flow is not important
- Other lower level forms are “closer to machine”
  - Stack machines
  - 3 address code

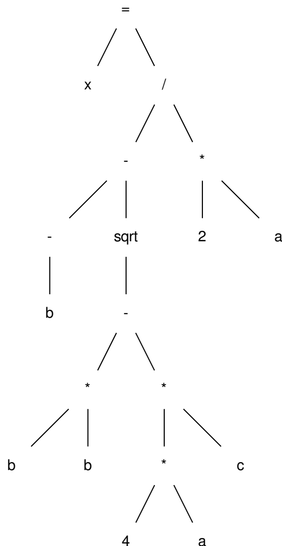
# Stack Machine

```
push a
push 2
mul
push c
push a
push 4
mul
mul
push b
push b
mul
sub
sqrt
push b
neg
sub
div
pop x
```

How do you produce stack machine code from an AST?

# Generating Stack Machine Code

```
push a
push 2
mul
push c
push a
push 4
mul
mul
push b
push b
mul
sub
sqrt
push b
neg
sub
div
pop x
```



# Stack machines

- Compact in size
    - Operands are implicit – on top of stack.
- Easy to execute
- BUT, fixed order of execution
    - Bad for parallelism
- Hard to analyze
- Nevertheless, widely used:
    - Java bytecode
    - Python bytecode
    - WebAssembly

# 3 address code

- 3 “addresses”
  - Two source operands
  - One destination operand
  - One operation
- Addresses are actually *names* generated by compiler
  - Or refer directly to variables

# Our example in 3-address code

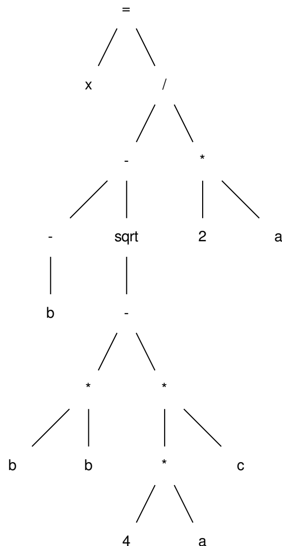
```
t1 <- -b

t2 <- b * b
t3 <- 4 * a
t4 <- t3 * c
t5 <- t2 - t4
t6 <- sqrt(t5)

t7 <- t1 - t6
t8 <- 2 * a
t9 <- t7 / t8

x <- t9
```

(Here ‘<–’ is $\leftarrow$, signifying assignment)

How do we produce 3-address code from the AST?

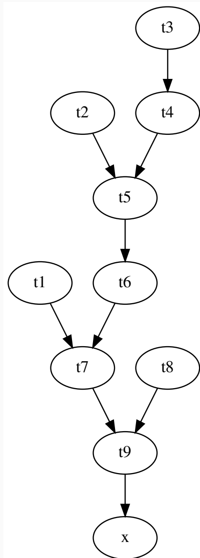
# Producing 3-address code

```
t1 <- -b

t2 <- b * b
t3 <- 4 * a
t4 <- t3 * c
t5 <- t2 - t4
t6 <- sqrt(t5)

t7 <- t1 - t6
t8 <- 2 * a
t9 <- t7 / t8

x <- t9
```



# Data Dependence Graphs (DDGs)

- DDGs track “data flow” as an acyclic graph
- Strict (partial) order in which operations must be performed
  - Can’t use a value that has not been calculated yet!
- But multiple orders may be allowed!
  - Topological sort
- Will revisit DDGs when we discuss instruction scheduling

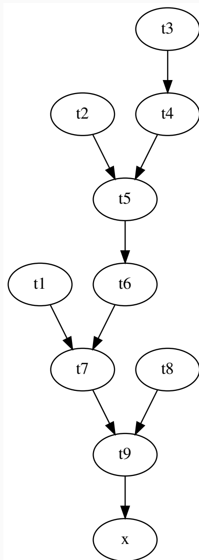


# DDG Example

```
t1 <- -b

t2 <- b * b
t3 <- 4 * a
t4 <- t3 * c
t5 <- t2 - t4
t6 <- sqrt(t5)

t7 <- t1 - t6
t8 <- 2 * a
t9 <- t7 / t8

x <- t9
```

# DDG Example, reordered by dependence

```
 # group 1
t1 <- -b
t2 <- b * b
t3 <- 4 * a
t8 <- 2 * a

 # must wait for t3
t4 <- t3 * c

 # must wait for t4 and t2
t5 <- t2 - t4

 # ...
t6 <- sqrt(t5)

t7 <- t1 - t6

t9 <- t7 / t8

x <- t9
```

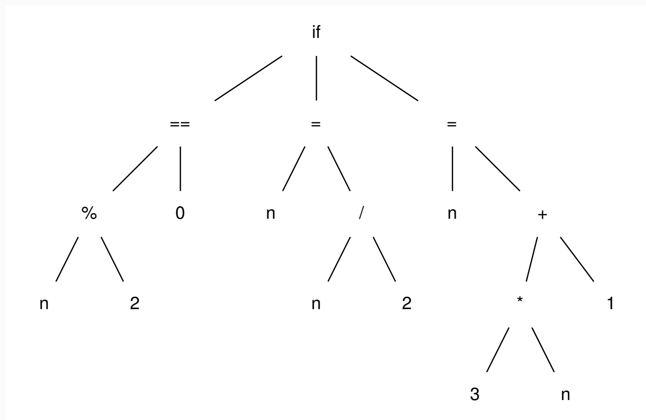


# Control structures in 3-address code

What should the 3 address code for the code below look like?

```
if n % 2 == 0:
   n = n / 2
else:
   n = 3 * n + 1
```

# The AST for if




- An `if` AST node has a `condition`, `true-code`, and `false-code`

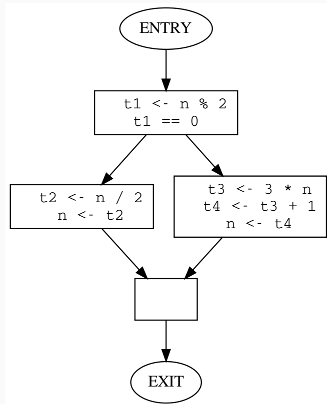
# 3-Address Code for if

```
  t1 <- n % 2
  tc <- t1 == 0
  if (tc == 0) goto L1

  t2 <- n / 2
  n <- t2
  goto L2

L1:
  t3 <- 3 * n
  t4 <- t3 + 1
  n <- t4

L2:
```

- 3-address code can contain:
    - conditional branches, usually just a comparison to zero
    - unconditional branches
    - labels

# Control Flow Graphs (CFGs)

- “Hybrid” representation
  - Linear code + Graph structure
- Each node in the CFG is a “basic block”
  - Linear code
  - Single entry, single exit
  - “Straight-line code”
- Most common form for analysis



## In this course

- We will write midend + some bits of a backend
- Input language: C
- Output language: C in 3-address form
  - Not assembly (maybe extra credit?)
- Using Python library `pycparser`

## For assignments, make sure to review

- Basic data structures
  - lists
  - trees
  - graphs
- Basic data structure traversals
  - Infix, prefix, postfix
  - Depth-first, breadth-first
- And how to implement them in Python
  - Using Python standard libraries is fine

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# Not-so-classic ‘Compiler’ Architectures

What is this code from TensorFlow doing?

```
a = tf.constant(2)
b = tf.constant(3)

with tf.Session() as sess:
    print("a=2, b=3")
    print("Addition with constants: %i" % sess.run(a+b))
    print("Multiplication with constants: %i" % sess.run(a*b))
```

https://github.com/aymericdamien/TensorFlow-Examples/blob/master/examples/1_Introduction/basic_operations.py

# Metaprogramming

- TensorFlow API builds a graph
  - directed, acyclic
  - similar to the DDG
  - very common technique
- When `sess.run` is called, graph is compiled and executed
- Advantages:
  - No syntax, no parsing!
- Disadvantages:
  - ?

# References

- Chapter 5 of Cooper and Turczon
    - Up to 5.4 in this lecture, but we will ultimately study the whole chapter