

EECS 583 – Advanced Compilers

Course Overview, Introduction to Control Flow Analysis

Winter 2023, University of Michigan

Jan 4, 2023

<https://web.eecs.umich.edu/~mahlke/courses/583w23>

Class Meeting Pattern

❖ Lecture

- » Mon/Wed 10:30-12:00
- » Attendance options:
 - In person: G906 Cooley
 - Live zoom
 - Recorded zoom session

❖ Discussion/Office hours

- » Wed 12:30-1:30, 1005 Dow
- » Only in-person is available
- » Attendance is optional
 - Homework specific material
 - Lecture catchup – this should be rare
 - Student questions

Lectures

❖ In-person lecture

- » Try to attend, get more out of the lecture
- » Masks are optional, please stay home if you have any symptoms!
- » May have some virtual classes during the semester

❖ Class will also be presented live on Zoom

- » Participate from home if you wish
- » Zoom videos also available

❖ Zoom info

- » Same link/password for all lectures, posted on course website
- » Separate link for GSI office hrs – same link/password for entire semester and both GSIs

Attending Class Virtually

- ❖ Lecture is synchronous and recorded
 - » Please try to attend live if you can
 - » We'll start a bit after 10:30 and end at 11:50
 - » **Keep your camera and mic muted**
 - **Critical to avoid disruptions**
- ❖ Asking questions on Zoom
 - » Type the word “question” in the chat box
 - » GSI will unmute you and you can ask question
 - » If you prefer not to speak, then just type out your question in chat and the GSI can ask it for you
 - » I will also pause regularly to ask if there are questions
 - » Discussion important in a grad class, so don't be bashful

About Me

- ❖ Mahlke = mall key
 - » But just call me Scott
- ❖ Been at Michigan since 2001
 - » Compiler guy who likes hardware
 - » Program optimization to make programs go faster
 - » Building custom hardware for high performance/low power
- ❖ Before this – HP Labs in Silicon Valley
- ❖ Before before – Grad student at UIUC
- ❖ Before ^ 3 – Undergrad at UIUC

More About Me

❖ 3 kids – 6, 6, and 4

» So if I show up to lecture half asleep, you know why!



Contact Information

- ❖ Email: mahlke@umich.edu
- ❖ Office hours
 - » Wed, 12:30-1:30 1005 Dow
 - » Or send me an email for an appointment
- ❖ Visiting office hrs
 - » Mainly help on classroom material, concepts, etc.
 - » I am an LLVM novice, so likely I cannot answer any non-trivial question
 - » See GSIs for LLVM details

583 GSI



- ❖ Aditya Vasudevan (adivasu@umich.edu)
- ❖ Office hours
 - » Tue 2-4pm, Wed 2-4pm, Thu 2-4pm
 - » Location: Zoom (link on course website, same link for the entire semester, passcode = eecs583)

Getting Help from the GSIs

- ❖ LLVM help/questions
- ❖ But, you will have to be independent in this class
 - » Read the documentation and look at the code
 - » Come to them when you are really stuck or confused
 - » They cannot and will not debug your code
 - » Helping each other is encouraged
 - » Use the class piazza group (GSIs will monitor)
- ❖ Virtual office hours on Zoom
 - » Considering having appointments along with open sessions

Class Overview

❖ This class is NOT about:

- » Programming languages
- » Parsing, syntax checking, semantic analysis
- » Handling advanced language features – virtual functions, ...
- » Frontend transformations
- » Debugging
- » Simulation

❖ Compiler backend

- » Mapping applications to processor hardware
- » Retargetability – work for multiple platforms (not hard coded)
- » Work at the assembly-code level (but processor independent)
- » Speed/Efficiency
 - How to make the application run fast
 - Use less memory (text, data), efficiently execute
 - Parallelize, prefetch, optimize using profile information

Background You Should Have

❖ 1. Programming

- » Good C++ programmer (essential)
- » Linux, gcc, emacs
- » Debugging experience – hard to debug with printf's alone – gdb!
- » Compiler system not ported to Windows

❖ 2. Computer architecture

- » EECS 370 is good, 470 is better but not essential
- » Basics – caches, pipelining, function units, registers, virtual memory, branches, multiple cores, assembly code

❖ 3. Compilers

- » Frontend stuff is not very relevant for this class, but good to know
- » Basic backend stuff we will go over fast
 - Non-EECS 483 people will have to do some supplemental reading

Textbook and Other Classroom Material

- ❖ No required text – Lecture notes, papers
- ❖ LLVM compiler system – we will use version 15.0.6
 - » LLVM webpage: <http://www.llvm.org>
 - » Read the documentation!
 - » LLVM users group
- ❖ Course webpage + course newsgroup
 - » <https://www.eecs.umich.edu/~mahlke/courses/583w23>
 - » Lecture notes – available the night before class
 - » Newsgroup – ask/answer questions, GSI and I will try to check regularly but may not be able to do so always
 - <http://www.piazza.com>

What the Class Will be Like

❖ Core backend stuff

- » Text book material – some overlap with 483
- » 2 homeworks to apply classroom material

❖ Research papers

- » Last 1/3rd of the semester, students take over
- » Select paper related to your project
- » Each project team - presents 1 paper. 12 min talk + 3 min Q&A.
- » Entire class is expected to watch presentations and grade presentations
- » You will need to attend live for at least your own presentation

What the “Virtual” Class Will be Like (2)

❖ Learning compilers

- » No memorizing definitions, terms, formulas, algorithms, etc
- » Learn by doing – Writing code
- » Substantial amount of programming
 - Fair learning curve for LLVM compiler
- » Reasonable amount of reading

❖ Classroom

- » Attendance – Best to join live, lots of examples solved in class
 - » Discussion important
 - Work out examples, discuss papers, etc
 - » Essential to stay caught up
 - » Extra meetings outside of class to discuss projects
-

Course Grading

- ❖ Yes, everyone will get a grade
 - » Distribution of grades, scale, etc - ???
 - » Most (hopefully all) will get A's and B's
 - » Slackers will be obvious
- ❖ Components
 - » Midterm exam – 25%
 - » Project – 45%
 - » Homeworks – 15%
 - » Paper presentation – 10%
 - » Class participation – 5%

Homeworks

- ❖ 1 preliminary (HW0), available on course webpage later today
 - » Get LLVM set up, nothing to submit
- ❖ 2 real homeworks
 - » 1 small & 1 harder programming assignment
 - » Design and implement something we discussed in class
- ❖ Goals
 - » Learn the important concepts
 - » Learn the compiler infrastructure so you can do the project
- ❖ Grading
 - » Working testcases?, Does anything work? Level of effort?
- ❖ Working together on the concepts is fine
 - » Make sure you understand things or it will come back to bite you
 - » Everyone must do and turn in their own assignment

Projects – Most Important Part of the Class

- ❖ Design and implement an “interesting” compiler technique and demonstrate its usefulness using LLVM
- ❖ Topic/scope/work
 - » 3-4 people per project (Other group sizes allowed in some cases)
 - » You will pick the topics (I have to agree)
 - » You will have to
 - Read background material
 - Plan and design
 - Implement and debug
- ❖ Deliverables
 - » Working implementation
 - » Project report: ~5 page paper describing what you did/results
 - » 15 min presentation at end (demo if you want)
 - » Project proposal (late Feb) scheduled with each group during semester

Types of Projects

- ❖ New idea
 - » Small research idea
 - » Design and implement it, see how it works
 - ❖ Extend existing idea
 - » Take an existing paper, implement their technique
 - » Then, extend it to do something small but interesting
 - Generalize strategy, make more efficient/effective
 - ❖ Implementation
 - » Take existing idea, create quality implementation in LLVM
 - » Try to get your code released into main LLVM system
 - ❖ Using other compilers/systems (GPUs, JIT, mobile phone, etc.) is possible
-

Topic Areas (You are Welcome to Propose Others)

❖ Automatic parallelization

- » Loop parallelization
- » Vectorization/SIMDization
- » Transactional memories/speculation
- » Breaking dependences

❖ Memory system performance

- » Instruction/data prefetching
- » Use of scratchpad memories
- » Data layout

❖ Reliability

- » Catching transient faults
- » Reducing AVF

❖ Customized hardware

- » High level synthesis
- » HW optimization

❖ Power

- » Instruction scheduling techniques to reduce power
- » Identification of narrow computations

❖ Streaming/GPUs

- » Stream scheduling
- » Memory management
- » Optimizing CUDA programs

❖ Security

- » Program analysis to identify vulnerabilities
- » Eliminate vulnerabilities via xforms

❖ Dynamic optimization

- » DynamoRIO
- » Run-time optimization

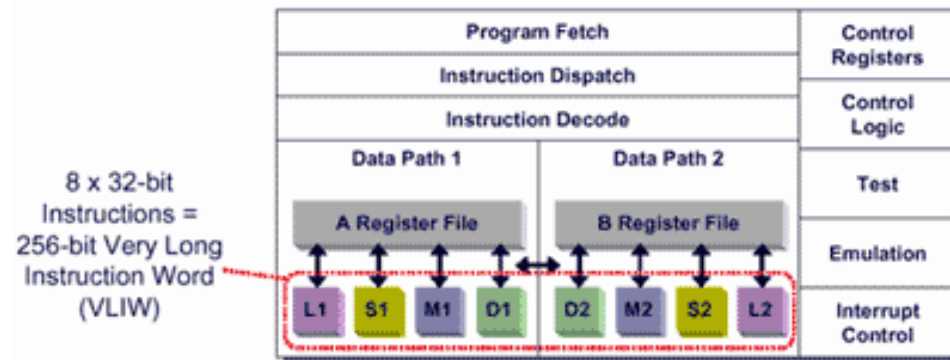
Class Participation

- ❖ Interaction and discussion is essential in a graduate class
 - » Try to join live if you can (not required)
 - » If you are here, don't just stare at the wall
 - » Be prepared to discuss the material
 - » Have something useful to contribute
- ❖ Opportunities for participation
 - » Research paper discussions – thoughts, comments, etc
 - » Saying what you think in project discussions outside of class
 - » Solving class problems, asking intelligent questions
 - » Helping answer questions on piazza!

Tentative Class Schedule (on course website)

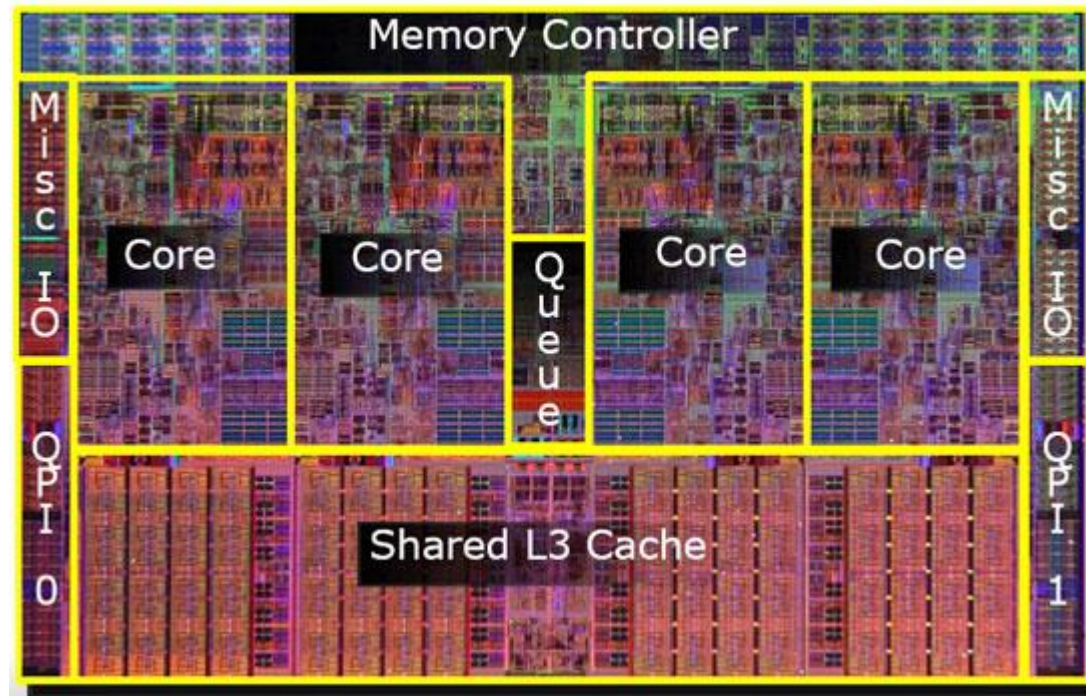
Week	Date	Topic
1 Mon	-	
Wed	Jan 4	Course intro, Control flow analysis, HW #0 out
2	Jan 9	Control flow analysis
	Jan 11	Control flow analysis, HW #0 due (nothing to turn in), HW #1 out
3	Jan 16	No class, MLK Day
	Jan 18	Control flow analysis
4	Jan 23	Dataflow analysis, HW #1 due
	Jan 25	Dataflow analysis, HW #2 out
5	Jan 30	SSA form
	Feb 1	Code optimization
6	Feb 6	Code optimization
	Feb 8	Code generation
7	Feb 13	Code generation
	Feb 15	Code generation, HW #2 due
8	Feb 20	Code generation
	Feb 22	Code generation, Advanced Topics (Parallelization)
9	Feb 27	No class, Spring Break
	Mar 1	No class, Spring Break
10	Mar 6	No regular class - Project proposals
	Mar 8	No regular class - Project proposals
11	Mar 13	Midterm Review
	Mar 15	Midterm Exam (Date is Tentative!)
12	Mar 20	Research paper presentations
	Mar 22	Research paper presentations
13	Mar 27	Research paper presentations
	Mar 29	Research paper presentations
14	Apr 3	Research paper presentations
	Apr 5	Research paper presentations
15	Apr 10	Research paper presentations
	Apr 12	Research paper presentations
16	Apr 17	No regular class – Finish projects
	-	
	Apr 17-21	Project demos

Target Processors: 1) VLIW/EPIC Architectures



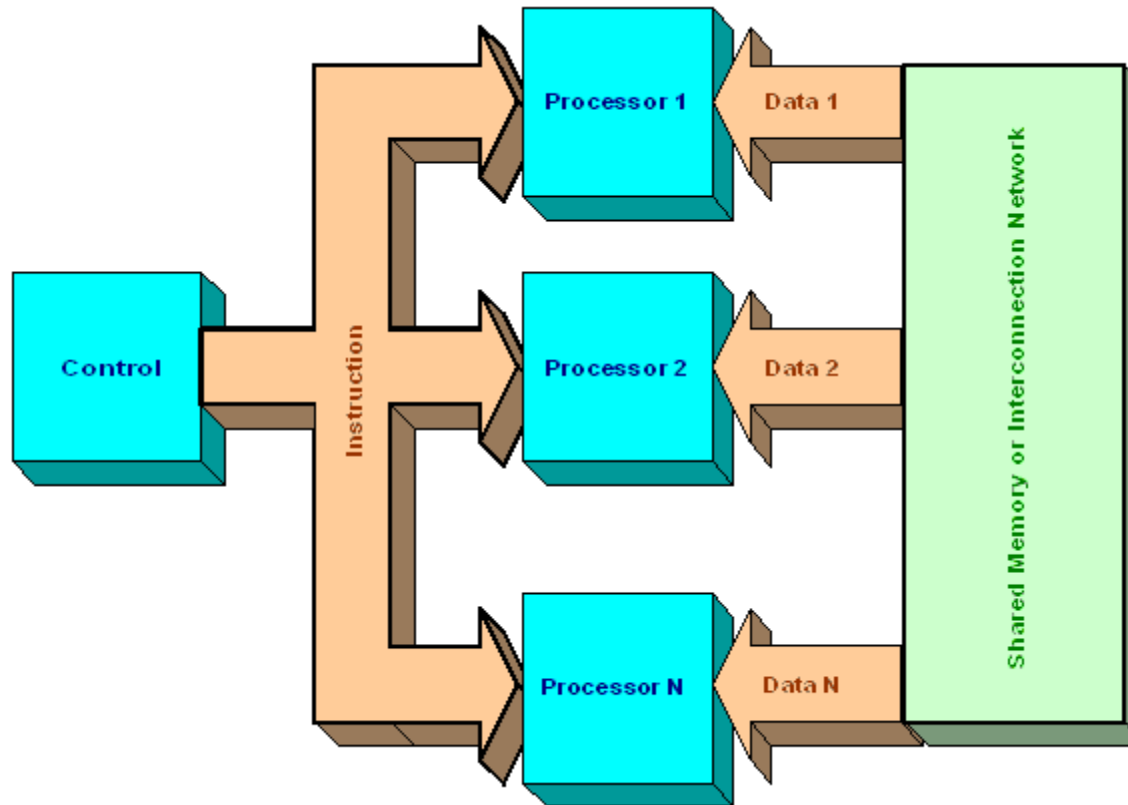
- ❖ VLIW = Very Long Instruction Word
 - » Aka EPIC = Explicitly Parallel Instruction Computing
 - » Compiler managed multi-issue processor
- ❖ Desktop
 - » IA-64: aka Itanium I and II, Merced, McKinley
- ❖ Embedded processors
 - » All high-performance DSPs are VLIW
 - Why? Cost/power of superscalar, more scalability
 - » TI-C6x, Philips Trimedia, Starcore, ST-200

Target Processors: 2) Multicore



- ❖ Sequential programs – 1 core busy, 3 sit idle
- ❖ How do we speed up sequential applications?
 - » Switch from ILP to TLP as major source of performance
 - » Memory dependence analysis becomes critical

Target Processors: 3) SIMD/GPU



- ❖ Do the same work on different data: GPU, SSE, etc.
- ❖ Energy-efficient way to scale performance
- ❖ Must find “vector parallelism”

So, lets get started... Compiler Backend IR – Our Input

❖ Variable home location

- » Frontend – every variable in memory
- » Backend – maximal but safe register promotion
 - All temporaries put into registers
 - All local scalars put into registers, except those accessed via &
 - All globals, local arrays/structs, unpromotable local scalars put in memory. Accessed via load/store.

❖ Backend IR (intermediate representation)

- » machine independent assembly code – really resource indep!
- » aka RTL (register transfer language), 3-address code
- » $r1 = r2 + r3$ or equivalently add r1, r2, r3
 - Opcode (add, sub, load, ...)
 - Operands
 - ◆ Virtual registers – infinite number of these
 - ◆ Literals – compile-time constants

First Topic: Control Flow Analysis

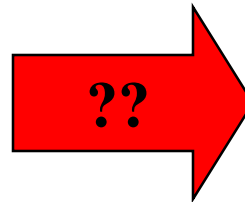
- ❖ Control transfer = branch (taken or fall-through)
- ❖ Control flow
 - » Branching behavior of an application
 - » What sequences of instructions can be executed
- ❖ Execution → Dynamic control flow
 - » Direction of a particular instance of a branch
 - » Predict, speculate, squash, etc.
- ❖ Compiler → Static control flow
 - » Not executing the program
 - » Input not known, so what could happen
- ❖ Control flow analysis
 - » Determining properties of the program branch structure
 - » Determining instruction execution properties

Basic Block (BB)

- ❖ Group operations into units with equivalent execution conditions
- ❖ Defn: Basic block – a sequence of consecutive operations in which flow of control enters at the beginning and leaves at the end without halt or possibility of branching except at the end
 - » Straight-line sequence of instructions
 - » If one operation is executed in a BB, they all are
- ❖ Finding BB's
 - » The first operation in a function starts a BB
 - » Any operation that is the target of a branch starts a BB
 - » Any operation that immediately follows a branch starts a BB

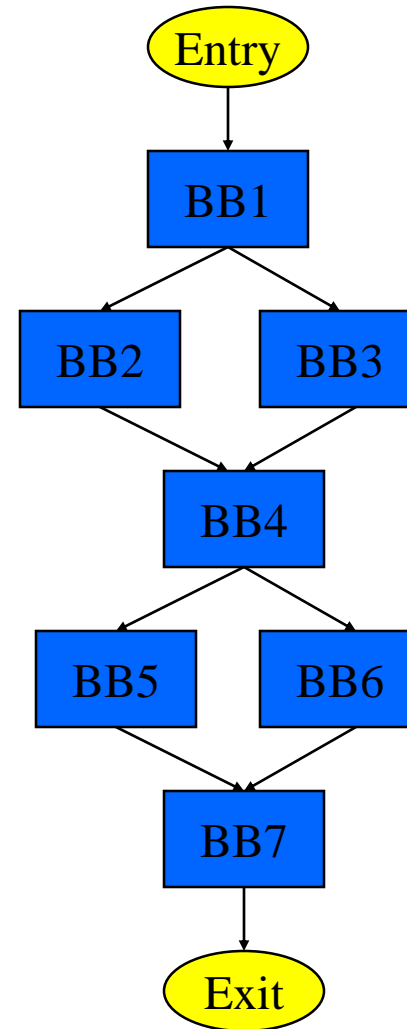
Identifying BBs - Example

L1: r7 = load(r8)
L2: r1 = r2 + r3
L3: beq r1, 0, L10
L4: r4 = r5 * r6
L5: r1 = r1 + 1
L6: beq r1 100 L3
L7: beq r2 100 L10
L8: r5 = r9 + 1
L9: jump L2
L10: r9 = load (r3)
L11: store(r9, r1)



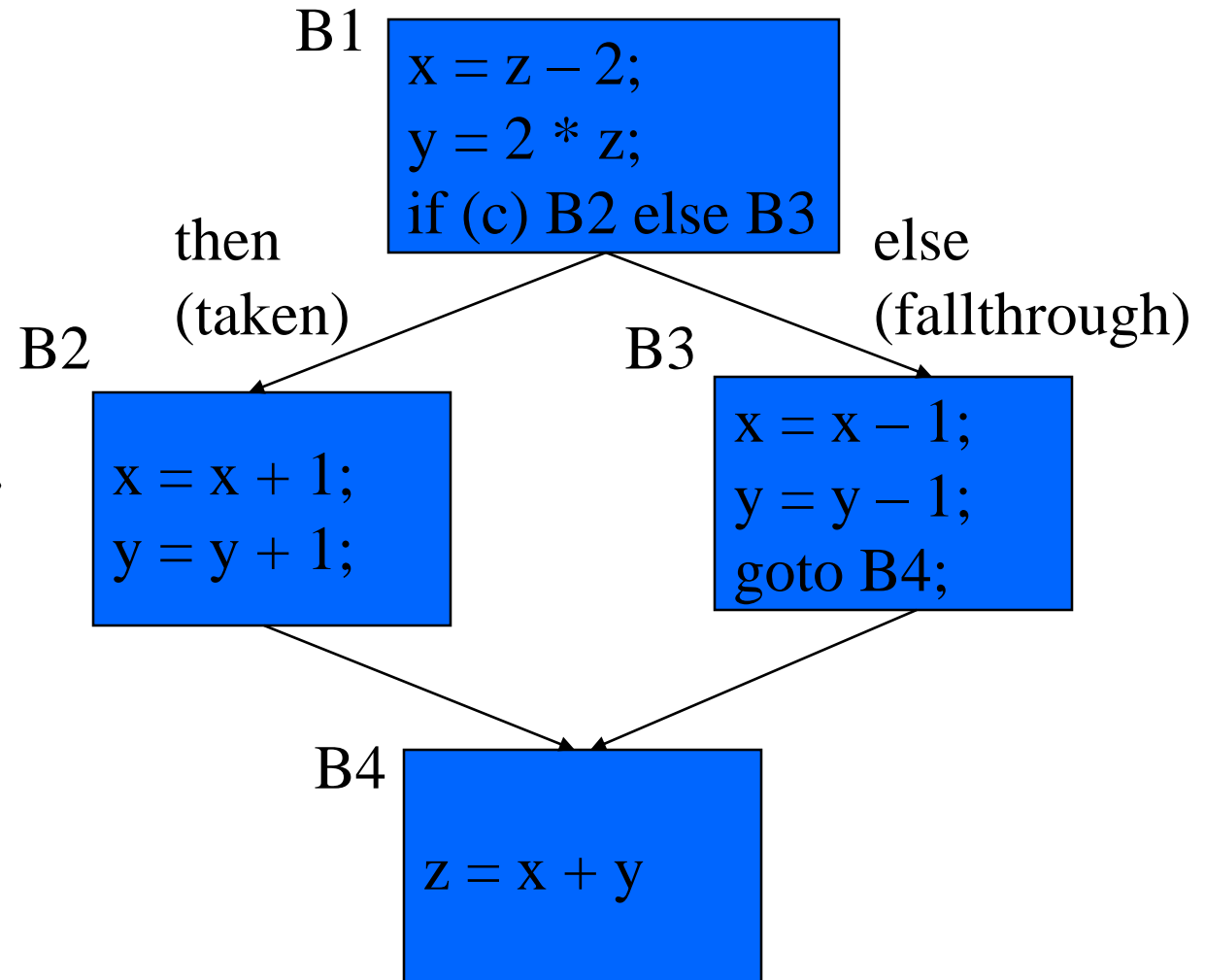
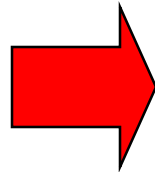
Control Flow Graph (CFG)

- ❖ Defn Control Flow Graph –
Directed graph, $G = (V, E)$
where each vertex V is a
basic block and there is an
edge E , $v_1 (BB1) \rightarrow v_2$
(BB2) if BB2 can
immediately follow BB1 in
some execution sequence
 - » A BB has an edge to all
blocks it can branch to
 - » Standard representation used
by many compilers
 - » Often have 2 pseudo vertices
 - entry node
 - exit node



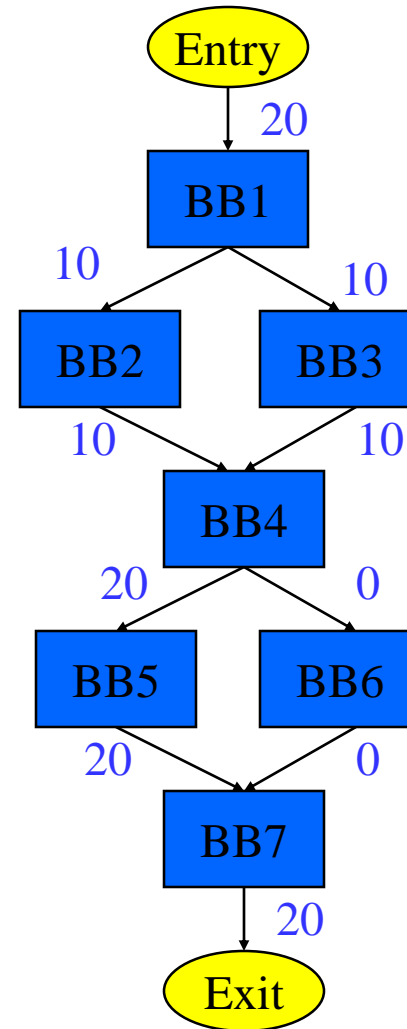
CFG Example

```
x = z - 2;  
y = 2 * z;  
if (c) {  
    x = x + 1;  
    y = y + 1;  
}  
else {  
    x = x - 1;  
    y = y - 1;  
}  
z = x + y
```



Weighted CFG

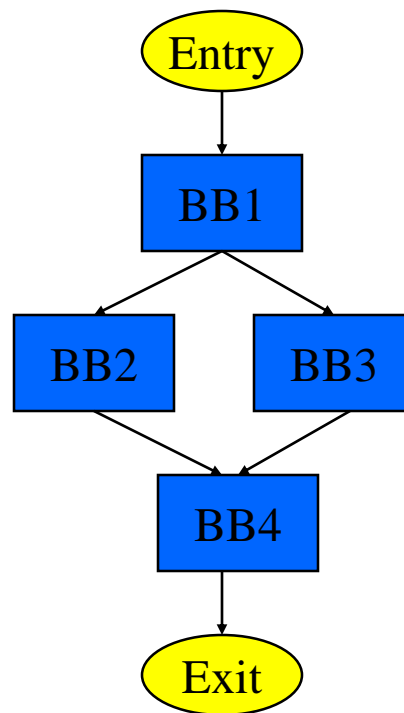
- ❖ Profiling – Run the application on 1 or more sample inputs, record some behavior
 - » **Control flow profiling**
 - edge profile
 - block profile
 - » Path profiling
 - » Cache profiling
 - » Memory dependence profiling
- ❖ Annotate control flow profile onto a CFG → weighted CFG
- ❖ Optimize more effectively with profile info!!
 - » Optimize for the common case
 - » Make educated guess



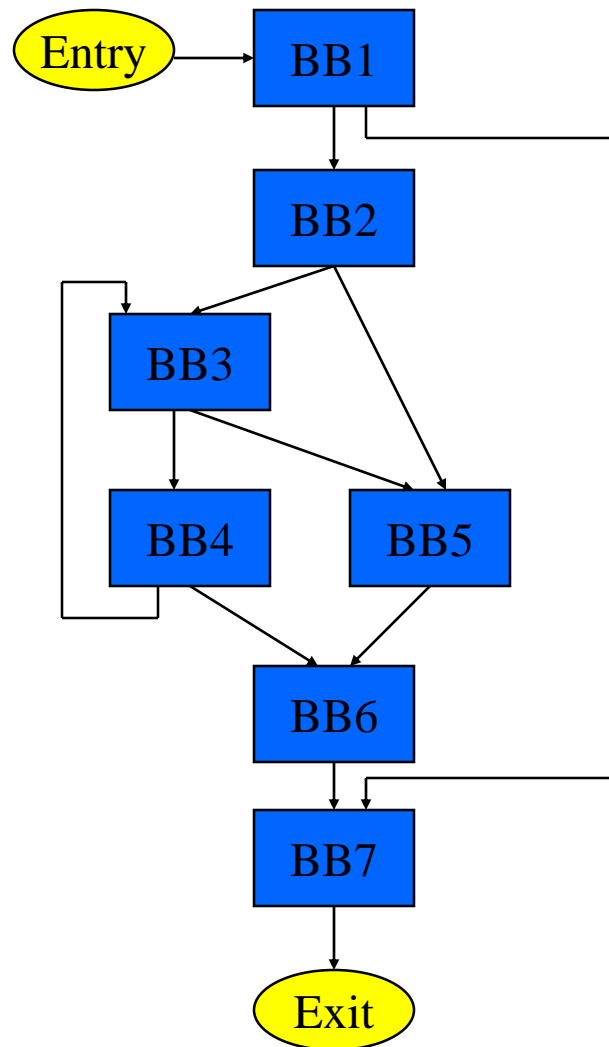
Property of CFGs: Dominator (DOM)

- ❖ Defn: Dominator – Given a CFG($V, E, \text{Entry}, \text{Exit}$), a node x dominates a node y , if every path from the Entry block to y contains x
- ❖ 3 properties of dominators
 - » Each BB dominates itself
 - » If x dominates y , and y dominates z , then x dominates z
 - » If x dominates z and y dominates z , then either x dominates y or y dominates x
- ❖ Intuition
 - » Given some BB, which blocks are guaranteed to have executed prior to executing the BB

Dominator Example 1



Dominator Example 2



Get Started ASAP!! Homework 0

- ❖ Go to <http://llvm.org>
- ❖ Setup LLVM 15.0.6 on the class server or your favorite Linux box
 - » For server, use the central version that is already set up
 - » For your own system, read the installation instructions
 - » See Aditya's post on piazza for detailed instructions
- ❖ Try to run it on a simple C program
- ❖ HW1 goes out next week and you need LLVM
- ❖ We will have 2 dedicated servers for class use
 - » `eecs583a/eecs583b.eecs.umich.edu`
 - » Everyone should have access later this week