CS 243: Advanced Compilers Course

Lecture 1

Introduction

I. Why Study Compilers?
II. Mathematical Abstractions: with Examples
III. Course Syllabus

Chapters 1.1-1.5, 8.4, 8.5, 9.1

Why Study Compilers?

Impact!

Techniques in compilers help all programmers

Compiler Technology: Key Programming Tool

Bridge the semantic gap between programmers and machines

Programming languages
- High-level programming languages
- Domain-specific languages
- Natural language

Programmers

↓

Programming Language

↓

Compilers

↓

Machine

Programming Tools
- Security
- Verification
- Binary translations

Computer architecture
- RISC vs CISC, Systolic arrays
- Locality: Caches, memory hierarchy
- Parallelism:
  - Instruction-level parallelism
  - Multi-processors

Compiler Study: a Software Engineering Course

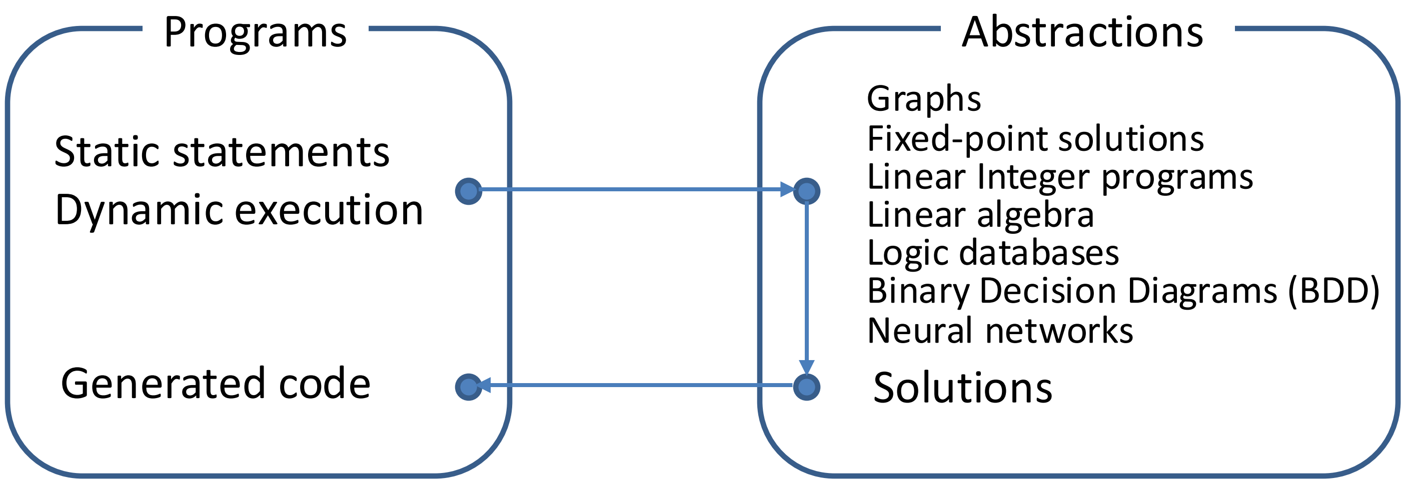
Trains Good Developers

- **Reasoning about programs makes better programmers**
- **Tool building: there are programmers and there are tool builders ...**
- **Excellent software engineering case study: Compilers are hard to build**
  - Input: all programs
  - Objectives:
- **Methodology for solving complex real-life problems**
  - Build upon mathematical / programming abstractions

Many years of research by many people to solve these problems elegantly.

Compilers: Where Theory Meets Practice

- Desired solutions are often NP-complete / undecidable
- Key to success: Formulate the right abstraction / approximation
  - Can't be solved by just pure hacking
    - theory aids generality and correctness
  - Can't be solved by just theory
    - experimentation validates & provides feedback to problem formulation
- Tradeoffs: Generality, power, simplicity, and efficiency



Why Study Compilers?

Impact!

Techniques in compilers help all programmers

Better Programmer

Reasoning about programs

Mathematical abstractions

Course Emphasis

- **Methodology: apply the methodology to other real-life problems**
  - Design
    - Problem statement: Which problem to solve?
    - New programming abstraction through domain-specific languages
  - Theory and Algorithm
    - Theoretical frameworks
    - Algorithms
  - Experimentation: Hands-on experience (Weekly programming/written homeworks)
- **Compiler knowledge:**
  - Non-goal: how to build a complete optimizing compiler
  - Important algorithms
  - Exposure to new ideas
  - Background to learn existing techniques

Interactive Instruction

- Compilers are not about memorizing facts
  - Open-book examinations
- Goal: teach how to derive the concepts
  - So you can apply to new problems
  - Lectures are interactive
  - Please come to class
  - The slides may miss main points to be emphasized in class!
    - These slides supplement lectures
    - They are not self contained!
    - They may contain mistakes, corrected in class!

The Rest of this Lecture

- Goal
  - Overview the course
  - Explain why I chose the topics
  - Emphasize abstraction methodology
- For each topic:
  - Motivate its importance
  - Show an example to illustrate the complexity
  - Describe the abstraction
  - Impact

1. Optimizing Compilers for High-Level Programming Languages

- Redundancy elimination
  - High-level programming languages introduce a lot of redundancies in programs that programmers are not aware of.
- Example:
  Bubblesort program that sorts array A allocated in static storage

```
for (i = n-2; i >= 0; i--) {
   for (j = 0; j <= i; j++) {
      if (A[j] > A[j+1]) {
         temp = A[j];
         A[j] = A[j+1];
         A[j+1] = temp;
      }
   }
}
```

Quiz: what is the best way to speed up this task?

Code Generated by the Front End

```
     i := n-2                       t13 = j+1
S5:  if i<0 goto s1                 t14 = 4*t13
     j := 0                         t15 = &A
s4:  if j>i goto s2                 t16 = t15+t14
     t1 = 4*j                       t17 = *t16     ;A[j+1]
     t2 = &A                        t18 = 4*j
     t3 = t2+t1                     t19 = &A
     t4 = *t3       ;A[j]           t20 = t19+t18  ;&A[j]
     t5 = j+1                      *t20 = t17      ;A[j]=A[j+1]
     t6 = 4*t5                      t21 = j+1
     t7 = &A                        t22 = 4*t21
     t8 = t7+t6                     t23 = &A
     t9 = *t8      ;A[j+1]          t24 = t23+t22
     if t4 <= t9 goto s3           *t24 = temp     ;A[j+1]=temp
     t10 = 4*j                  s3: j = j+1
     t11 = &A                       goto S4
     t12 = t11+t10              S2: i = i-1
     temp = *t12   ;temp=A[j]       goto s5
                                s1:
```

(***t4=*t3*** *means read memory at address in* ***t3*** *and write to* ***t4****:*
****t20=t17****: store value of* ***t17*** *into memory at address in* ***t20****)*

After Optimization

Result of applying:

global common subexpression

loop invariant code motion

induction variable elimination

dead-code elimination

to all the scalar and temp variables

These traditional optimizations can make a big difference!

```
     i = n-2
     t27 = 4*i
     t28 = &A
     t29 = t27+t28
     t30 = t28+4
S5:  if t29 < t28 goto s1
     t25 = t28
     t26 = t30
s4:  if t25 > t29 goto s2
     t4 = *t25          ;A[j]
     t9 = *t26          ;A[j+1]
     if t4 <= t9 goto s3
     temp = *t25        ;temp=A[j]
     t17 = *t26         ;A[j+1]
     *t25 = t17         ;A[j]=A[j+1]
     *t26 = temp        ;A[j+1]=temp
s3:  t25 = t25+4
     t26 = t26+4
     goto S4
S2:  t29 = t29-4
     goto s5
s1:
```

DataFlow Framework

- High-level programming languages
  - Need many optimizations to be efficient

- Data flow
  - A general framework
    - Finds fixed-point solution to a set of recurrence equations
    - Monotonicity

  - Theory: prove correctness properties once and for all
  - Implementation: same code reused

Summary

Topic	Abstraction	Impact
Data flow optimizations 1970-1980s	Graphs Recurrent equations Fixed-point	High-level programming without loss of efficiency.

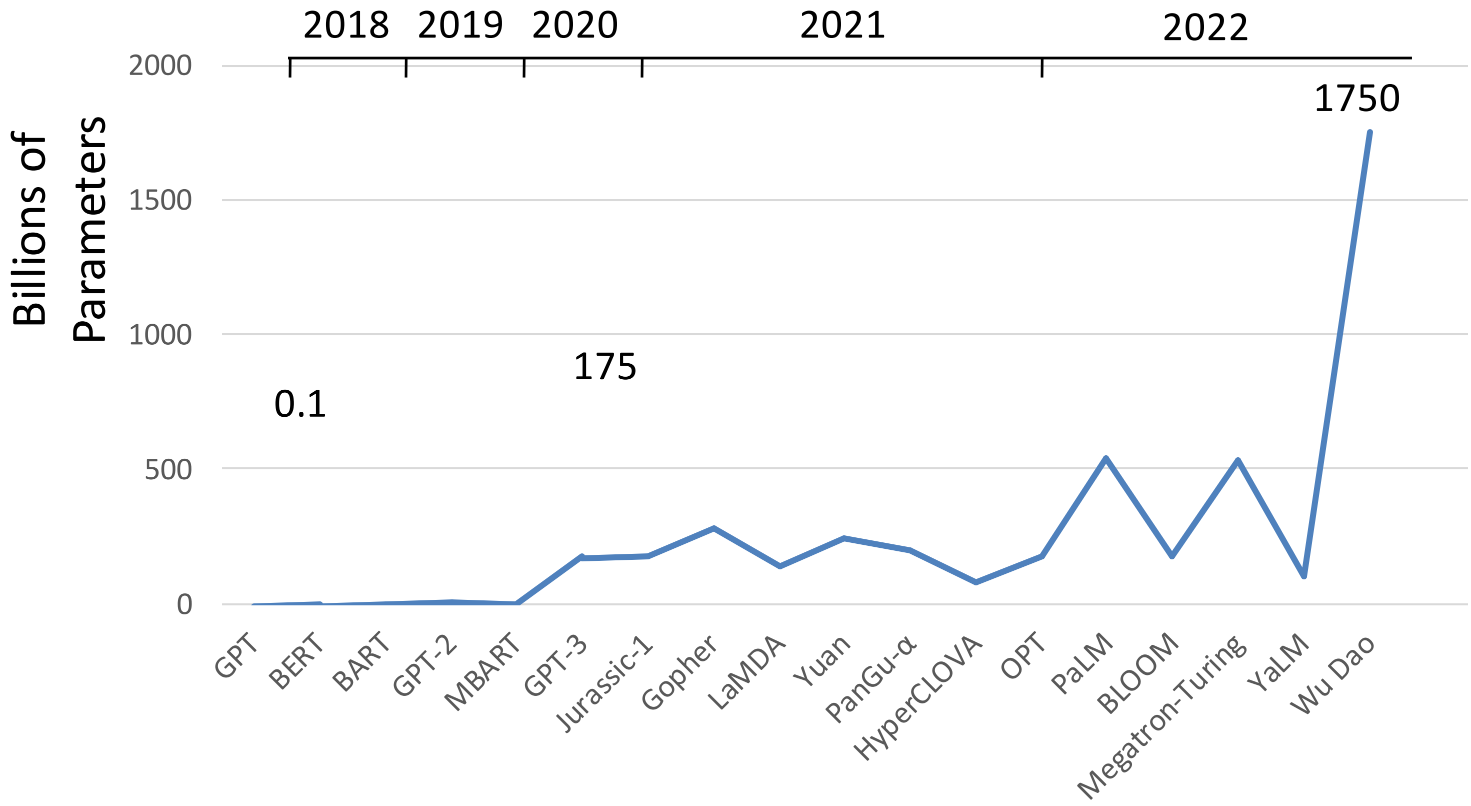
2. High Performance Computing / Machine Learning

- Large Language Models (LLMs)
- GPT-3 in 2020
  - Trained to predict the next word
  - Unsupervised: 45 TB of Internet text
  - 175 Billion parameters
- Training
  - 10,000 V100 GPUs ($4,600,000)
  - 1287000 KWh
  - 9 days

Trends of LLMs

YaLM & GPT-4 (3/14/2023)

- Multimodal: text, images



Nvidia Volta GV100 GPU

21B transistors

815 mm^2

1455 Mhz

80 Stream Multiprocessors (SM)

https://wccftech.com/nvidia-volta-tesla-v100-cards-detailed-150w-single-slot-300w-dual-slot-gv100-powered-pcie-accelerators/

In Each SM

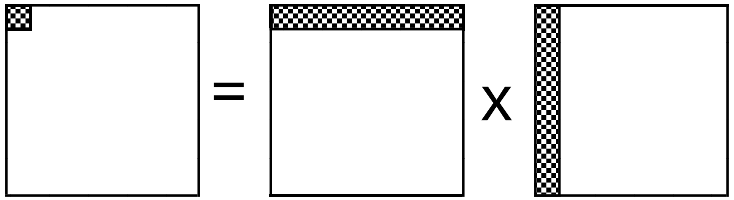
64 FP32 cores
64 int cores
32 FP64 cores
8 Tensor cores

Tensor Cores
D = A x B + C; A, B, C, D are 4x4 matrices
4 x 4 x 4 matrix processing array
1024 floating point ops / clock

FP32: 15 TFLOPS
FP64: 7.5 TFLOPS
Tensor: 120 TFLOPS

https://wccftech.com/nvidia-volta-tesla-v100-cards-detailed-150w-single-slot-300w-dual-slot-gv100-powered-pcie-accelerators/

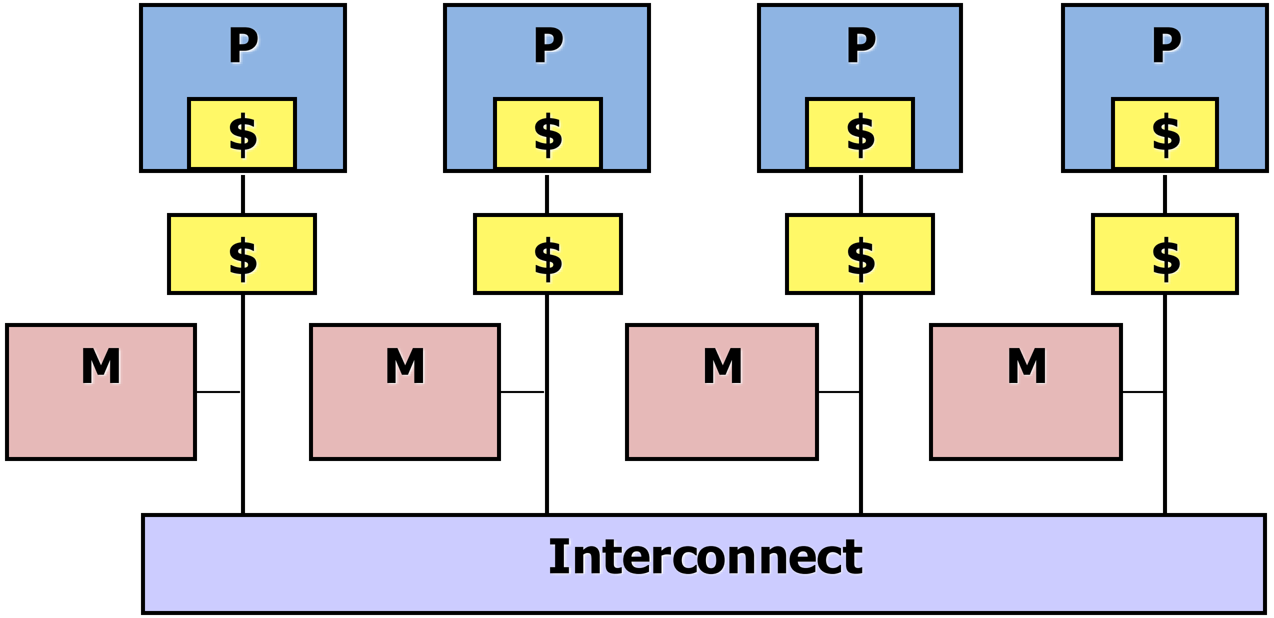
Matrix Multiplication




```
for (i = 0; i < n; i++) {
   for (j = 0; j < n; j++) {
       for (k = 0; k < n; k++) {
          Z[i,j] = Z[i,j] + X[i,k]*Y[k,j];
}}}
```

- n^3 computation
- n^2 threads of parallelism
- 2 memory operations per multiply-add operation
- Bottleneck: memory operations

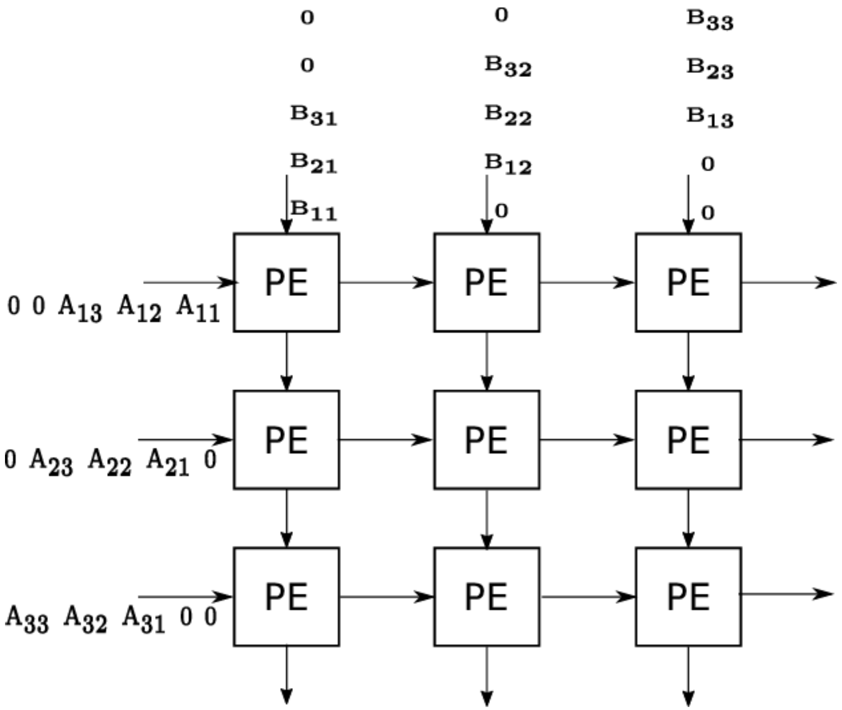
Multiprocessor Architecture



- Memory accesses are much more expensive than multiply-add
- Interconnect becomes a bottleneck – scalability!

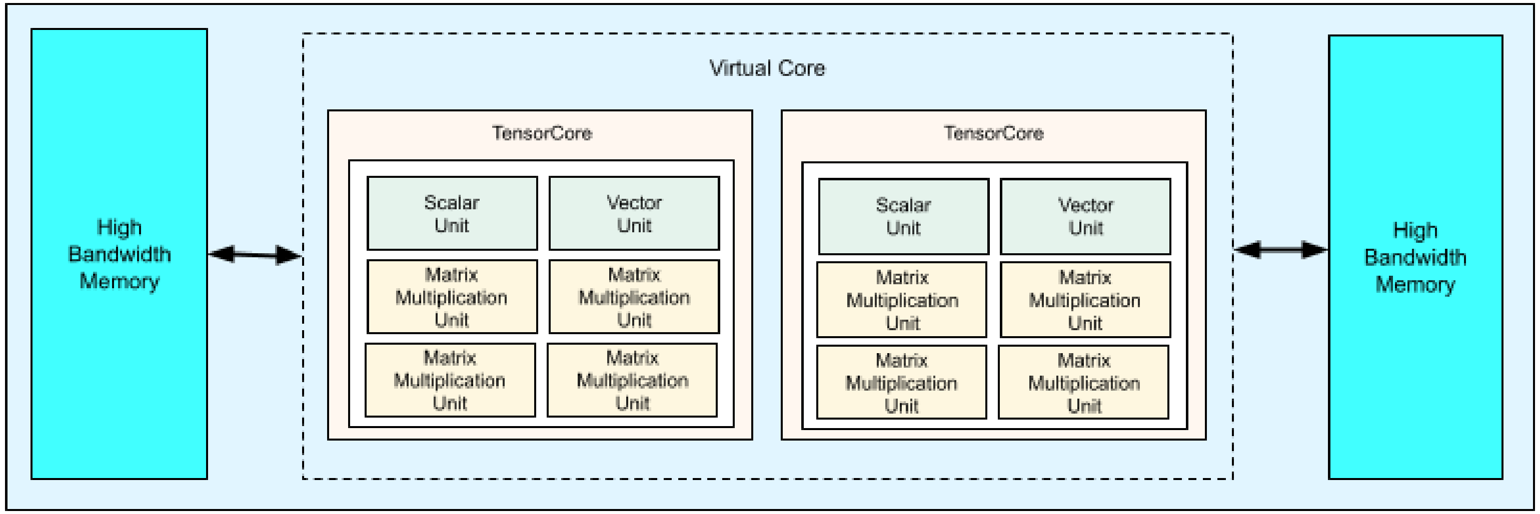
Systolic Arrays

- Introduced by Kung and Leiserson in 1978
- Special-purpose computer architecture for specific algorithms
- Processor interconnect matches algorithm communication pattern
- Eliminates the memory bottleneck
- TPU: 128 x 128 multiply/accumulators in a systolic array



Google TPU-v4 chips, 2022

TPU v4 chip

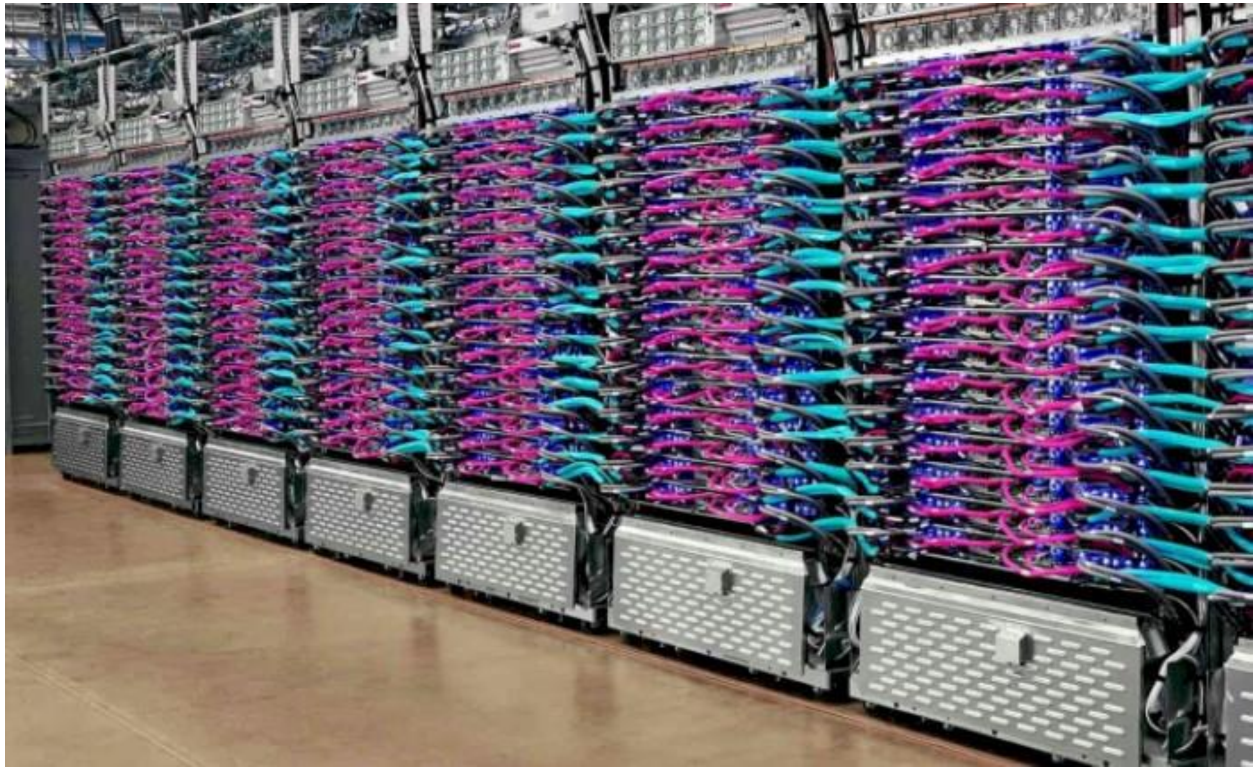


Matrix multiplication unit: 128 x 128 multiply/accumulators in a systolic array

Peak compute per chip	275 teraflops
Min/mean/max power	90/170/192 W
TPU pod size	4096 chips
Peak compute per pod	1.1 exaflops

https://cloud.google.com/tpu/docs/system-architecture-tpu-vm

Google TPU-v4 System



Google PaLM: 540B parameters in large language models
Using 6144 TPU v4 chips (1.7 exaflops)

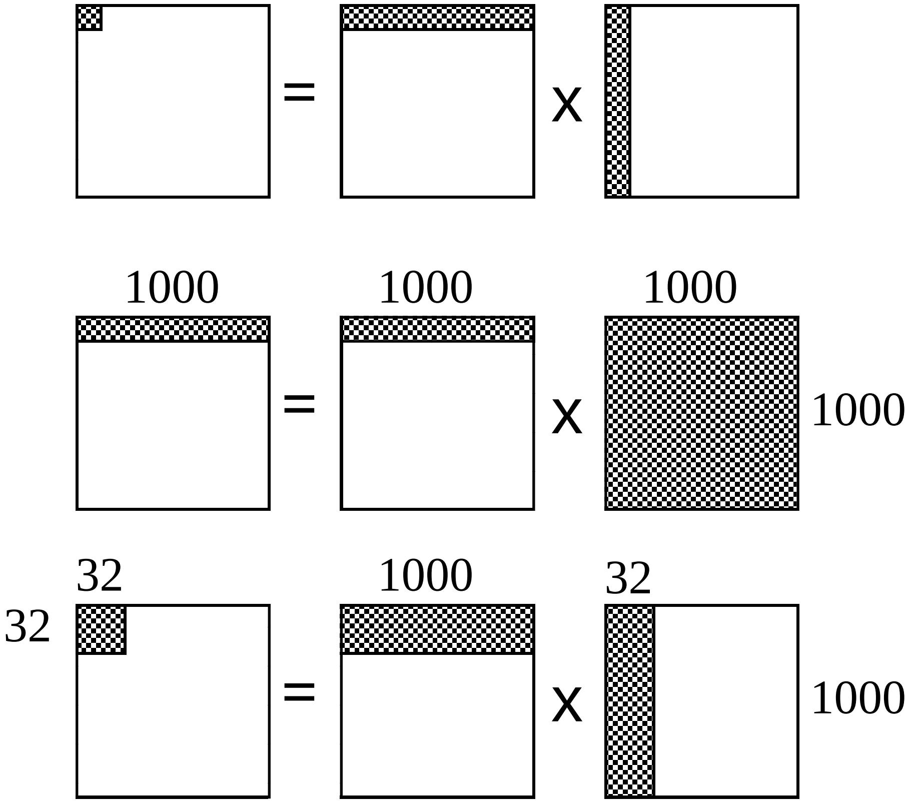
Principle to Successful Parallelism

- Parallel execution can be slower than sequential execution
  – Because of communication overhead!

- Goal: maximize parallelism and minimize communication

- Principles applicable to uniprocessors (caches) and multiproessors

Blocking for Matrix Multiplication



Data Accessed

1002000

65024

Blocking with Matrix Multiplication

- Original program

```
for (i = 0; i < n; i++) {
  for (j = 0; j < n; j++) {
     for (k = 0; k < n; k++) {
        Z[i,j] = Z[i,j] + X[i,k]*Y[k,j];
     }}}
```

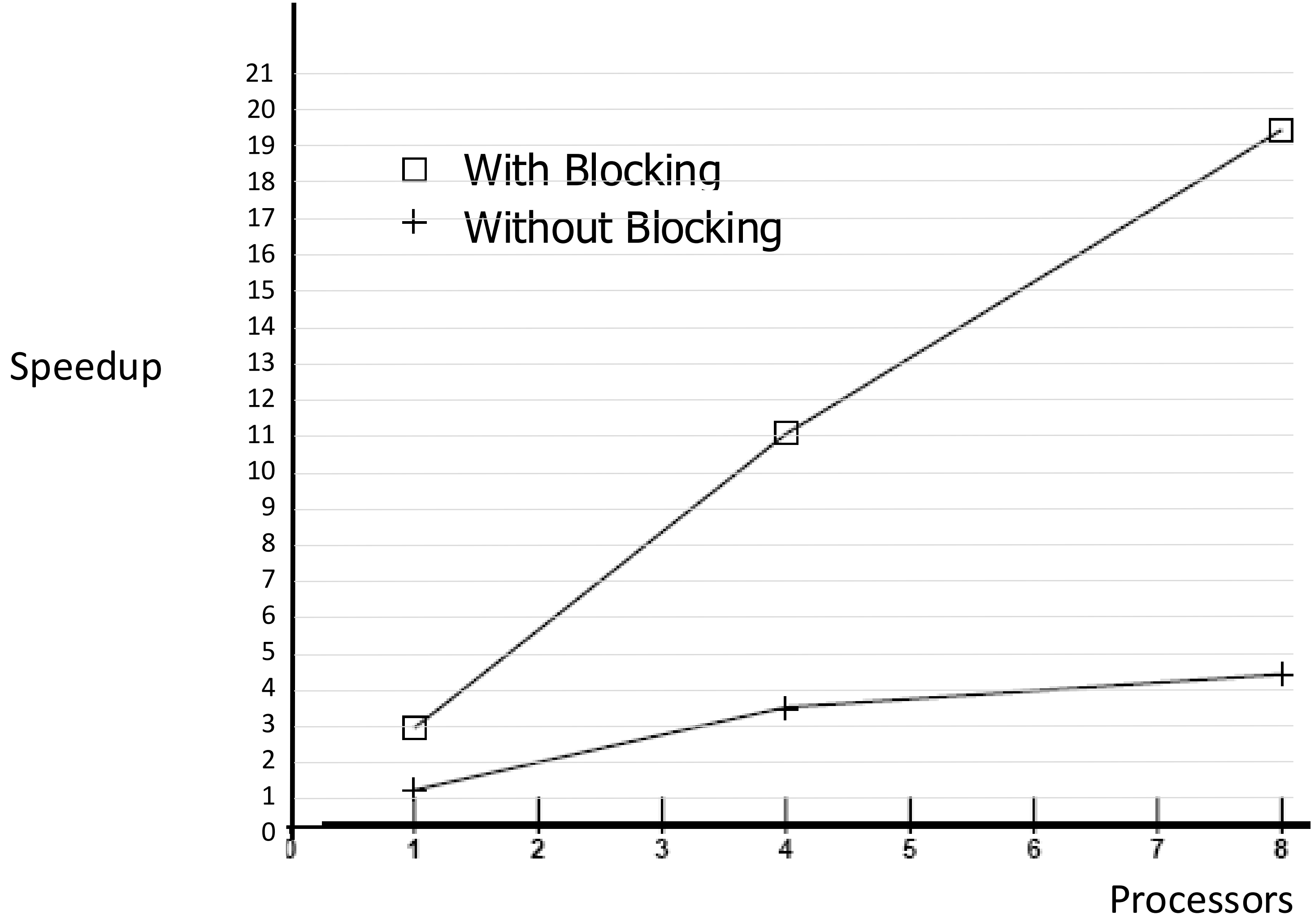
- Stripmine 2 outer loops

```
for (ii = 0; ii < n; ii = ii+B) {
  for (i = ii; i < min(n,ii+B); i++) {
    for (jj = 0; jj < n; jj = jj+B) {
      for (j = jj; j < min(n,jj+B); j++) {
         for (k = 0; k < n; k++) {
            Z[i,j] = Z[i,j] + X[i,k]*Y[k,j];
     }}}
```

- Permute loops

```
for (ii = 0; ii < n; ii = ii+B) {
 for (jj = 0; jj < n; jj = jj+B) {
   for (k = 0; k < n; k++) {
      for (i = ii; i < min(n,ii+B); i++) {
        for (j = jj; j < min(n,jj+B); j++) {
          Z[i,j] = Z[i,j] + X[i,k]*Y[k,j];
}}}
```

Experimental Results



Affine Framework

- Many useful loop transformations for locality & parallelism
  - Loop interchange, reversal, skewing
  - Loop fusion, fission
  - Blocking

- Affine Transformations
  - Inspired by systolic arrays
  - For dense matrix computations
  - A general framework
    - Geometric transforms (linear algebra)
    - Maximizes parallelism and minimizes communication by solving linear inequality constraints

Summary

Topic	Abstraction	Impact
Data flow optimizations 1970-1980s	Graphs Recurrent equations Fixed-point	High-level programming without loss of efficiency.
Parallelism and locality optimizations 1980-1990s	Integer linear programming Linear algebra	Hide complexity from programmers Machine independence code. Systolic arrays.

3. Garbage Collection

- Automatic memory management
  - Hugely improves program robustness and developer productivity

- Original: Naïve stop-the-world garbage collection
  - Stops the program to trace the reachability of all the objects

- Key optimizations → greatly reduce pause time
  - Incremental: break up GC in time
  - Partial: break up GC in space

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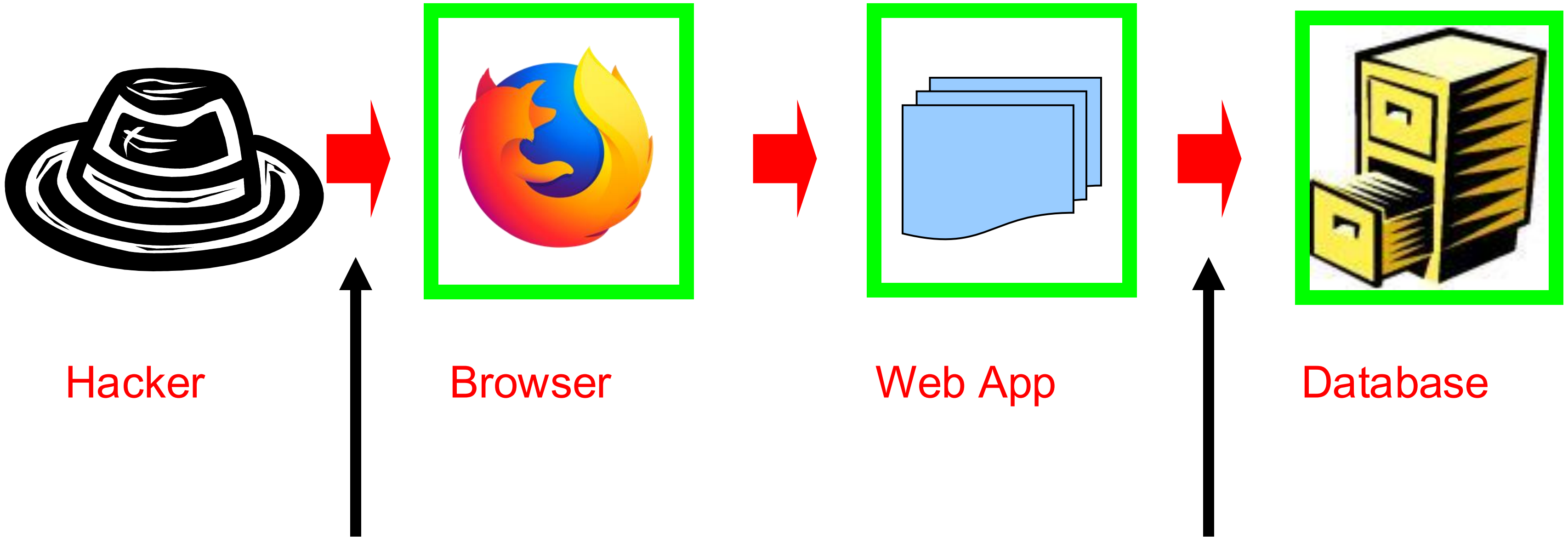
4. Pointer Alias Analysis Example: SQL Injection Errors



Give me Bob’s credit card #
Delete all records

SQL Injection Pattern

User supplies text

```
p1 = req.getParameter();
...
stmt.executeQuery(p2);
```

Text controls the database

Pointer analysis: can *p1* and *p2* point to the same object?

In Practice

ParameterParser.java:586
String session.ParameterParser.getRawParameter(String name)

```
public String getRawParameter(String name)
        throws ParameterNotFoundException {
        String[] values = request.getParameterValues(name);
        if (values == null) {
            throw new ParameterNotFoundException(name + " not found");
        } else if (values[0].length() == 0) {
            throw new ParameterNotFoundException(name + " was empty");
        }
        return (values[0]);
    }
```

ParameterParser.java:570
String session.ParameterParser.getRawParameter(String name, String def)

```
public String getRawParameter(String name, String def) {
    try {
      return getRawParameter(name);
    } catch (Exception e) {
      return def;
    }
}
```

In Practice (II)

ChallengeScreen.java:194
Element lessons.ChallengeScreen.doStage2(WebSession s)

```
String user = s.getParser().getRawParameter(USER, "");
StringBuffer tmp = new StringBuffer();
tmp.append("SELECT cc_type, cc_number from user_data WHERE
userid = '");
tmp.append(user);
tmp.append("'");
query = tmp.toString();
Vector v = new Vector();
try
{
  ResultSet results = statement3.executeQuery(query);
...
```

Automatic Conservative Analysis Generation with Context-Sensitive & Flow-Insensitive Pointer Analysis

Programmer:
Security analysis
in 10 lines

PQL

↓

Compiler Writer:
Ptr analysis in 10 lines

Datalog

↓

bddbddb
(**BDD**-**b**ased
deductive **d**ata**b**ase)
with
Active Machine Learning

1000s of lines
1 year tuning

BDD operations

BDD (Binary Decision Diagrams): 10,000s-lines library

SMT Example: Out-of-Bound Array Access

Program Assume data array bound is [0, N-1]

```
1 void ReadBlocks(int data[], int cookie)
2 {
3   int i = 0;
4   while (true)
5   {
6      int next;
7      next = data[i];
8      if (!(i < next && next < N)) return;
9      i = i + 1;
10     for (; i < next; i = i + 1){
11        if (data[i] == cookie)
12          i = i + 1;
13        else
14          Process(data[i]);
15     }
16   }
17 }
```

$(0 \leq i \wedge i < N)$

When is the array access in line 7 out of bound?

-- after data[i] == cookie, i = I + 1

Satisfiability Modulo Theories (SMT)

- Satisfiability
  - the problem of determining whether a formula has a model (an assignment that makes the formula true)
- SAT: Satisfiability of **propositional formulas**
  - A model is a truth assignment to Boolean variables
  - SAT solvers: check satisfiability of propositional formulas
    - Decidable, NP-complete
- SMT: Satisfiability modulo theories
  - Satisfiability of first-order formulas containing operations from background theories such as arithmetic, arrays, uninterpreted functions, etc.
- SMT Solvers:
  - check satisfiability of SMT formulas with respect to a theory

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Garbage collection 1990-2000s	Incremental and partial GC	Remove manual memory management
Program analysis for correctness 1990-2020s	Satisfiability modulo theories (SMT) Pointer Alias Analysis	Improve program robustness Save programmers debugging time.

5. NLP: Natural Language Processing

- Large language models (LLMs) e.g. GPT-3, chatGPT

1. **Help programmers with their task**
   - **Writing ”popular” programs from a description**
   - Example: website

     “*I would like you to act as a frontend web developer. For the project, you’ll code a new website using these tools: HTML, Bootstrap framework using the CDN for CSS and JavaScript. The website should be mobile-friendly and responsive. It should also include the most recent version of Twitter Bootstrap CSS classes in the site structure for layout and style. When it’s all done, there should be a single HTML file. You should also include a navigation menu with internal links to the headings within the page content. Do not provide explanations for any of the code you write.*”

https://themeisle.com/blog/how-to-use-chatgpt-to-build-a-website/#gref

NLP: Natural Language Processing

- Large language models (LLMs) e.g. GPT-3, chatGPT

1. **Help programmers with their task**
   - **Writing ”popular” programs from a description.**
   - **Improving programmers’ productivity with autocompletion**
     - As you code, or from your comments
     - OpenAI codex
       - Trained to predict the next word
         on the internet corpus, open-source code.

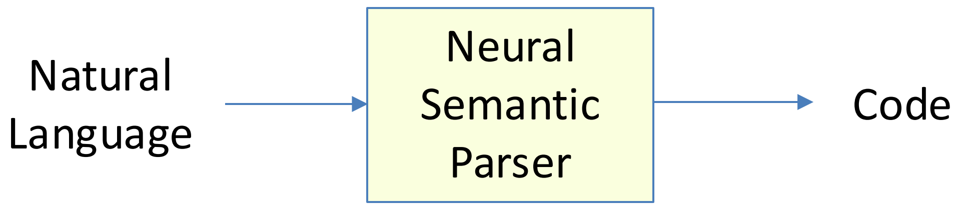
https://themeisle.com/blog/how-to-use-chatgpt-to-build-a-website/#gref

NLP: Natural Language Processing

- Large language models (LLMs) e.g. GPT-3, chatGPT

1. Help programmers with their tasks (Not a focus in this course)
   - Writing "popular" programs from a description.
   - Improving programmers' productivity with autocompletion

2. **End user programming (Focus in this course)**
   - Let *everybody* program with the highest-level programming language



Example: A YelpBot

- Yelp: API access to databases, which include reviews
- Created a new DSL: SUQL (structured and unstructured query language)

SUQL

"SELECT *, summary(reviews)
FROM restaurants WHERE
'szechuan' = ANY (cuisines) AND
location = "Palo Alto" AND
answer(reviews, 'does this restaurant serve spicy food?') = 'Yes' LIMIT 1;"

"SELECT answer(reviews, 'does this restaurant have non-spicy options?')
FROM restaurants
WHERE name ILIKE 'Taste' AND
location = 'Palo Alto';"

End-User Natural Language Programming

- New DSL designed for natural language programming
- Neural semantic parser: Use LLMs (with fine-tuning)
- Examples
  - SUQL: Structured and Unstructured Data Queries
    - Using LLMs as a subroutine
    - Optimizing compiler

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End user programming in natural language 2010-2020s	Neural semantic parser	New generation of natural, powerful user interfaces

Best of time-tested concepts in compilers!

Tentative Course Schedule

1	Course Introduction	
2	Data Flow Optimizations	Data-flow analysis: introduction
3		Data-flow analysis: theoretic foundation
4		Optimization: constant propagation
5		Optimization: redundancy elimination
6	Machine Dependent Optimizations	Register allocation
7		Instruction scheduling
8		Software pipelining
9	Loop Transformations	Parallelization
10		Loop transformations
11		Pipelined parallelism
12		Locality + parallelism
13	Satisfiability Modulo Theories	Static single assignment & SMT intro
14		SMT solvers
15	Garbage Collection	Advanced techniques
16	Pointer Analysis	Context-sensitive & flow-insensitive analysis
17	Conversational Interface to Hybrid Data Sources	Natural language → SUQL (Structured & unstructured query language)

Homework

- **Due Wednesday (no need to hand in)**
- Read Chapter 9.1 for introduction of the optimizations
- Work out the example on pages 10-12 in this handout.