CS536 Introduction to Advanced Compiler

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Outline

- Course Structure
- Pre-requisite
- Reference Books
- Grading Policy and Assignments
- Introduction and Motivation to course

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Why to study compiler?

Impact!

Techniques in compilers helps all programmers

Compiler technology

- **Bride gap between HLL and Machine**

Concept of Prog. Lang.
- High Level Prog. Lang.
- Domain Specific Lang.
- Natual Lang.

Concept of Comp. Arch.
- RISC vs CISC
- Locality: Cache, memory hierarchy
- Parallelism : Instruction level, Thread level

Programmers

↓

Prog. Language

Compilers

↓

Machine Code

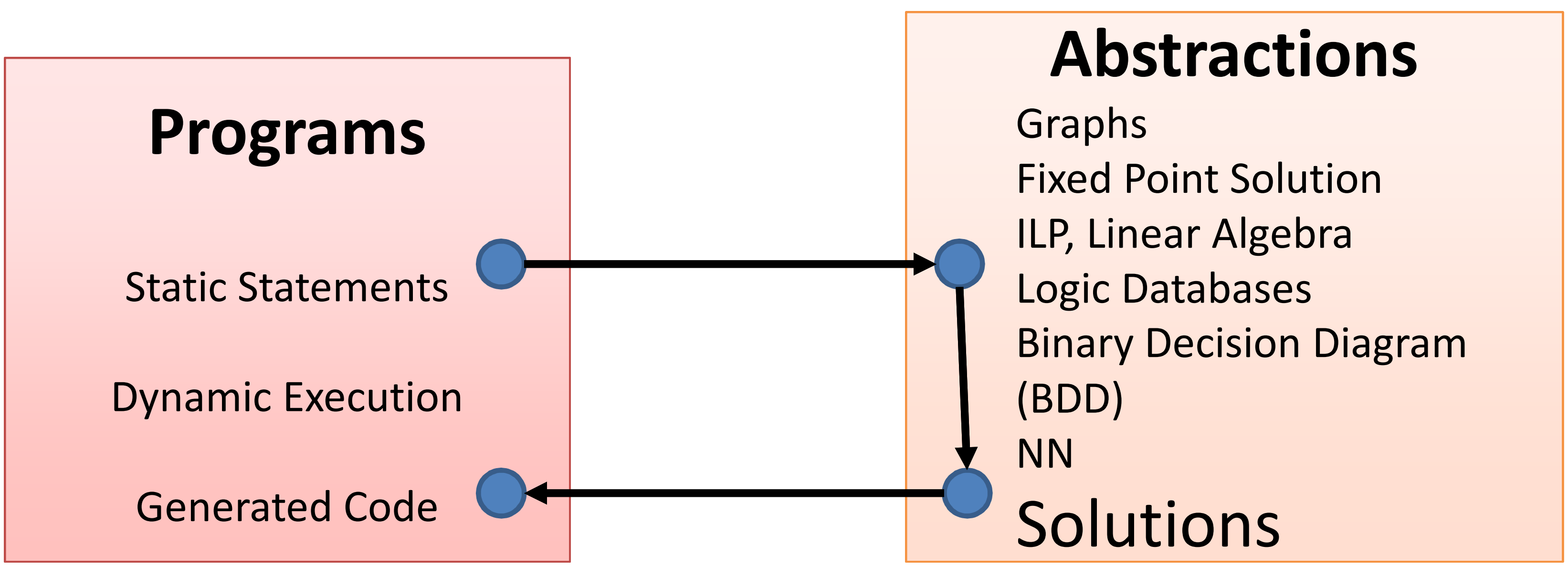
Prog. Tools
- Binary Translation
- Security

Compiler Study 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

Compilers: Where theory meets practice

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



Compiler Study Trains Good Developers

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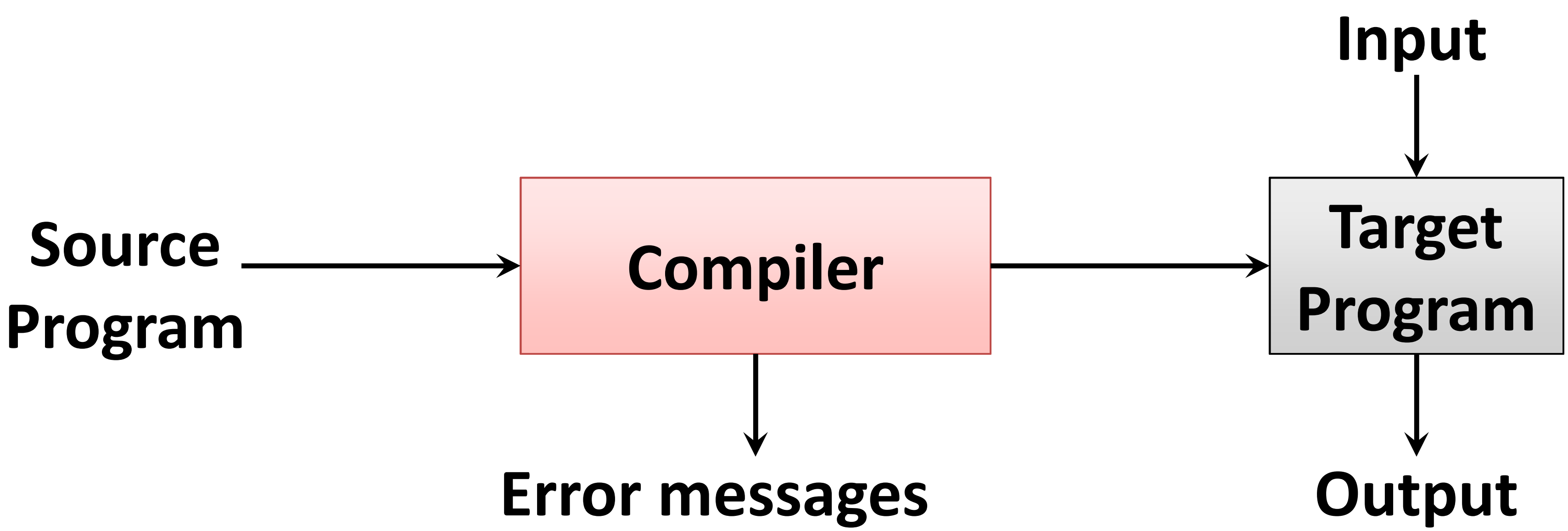
How Can the Compiler Improve Performance?

Execution time = Operation count * Cycles per operation

- Minimize the number of operations
  - arithmetic operations, memory accesses
- Replace expensive operations with simpler ones
  - e.g., replace 4 - cycle multiplication with 1 - cycle shift
- Minimize cache misses
  - both data and instruction accesses
- Perform work in parallel
  - instruction scheduling within a thread
  - parallel execution across multiple threads

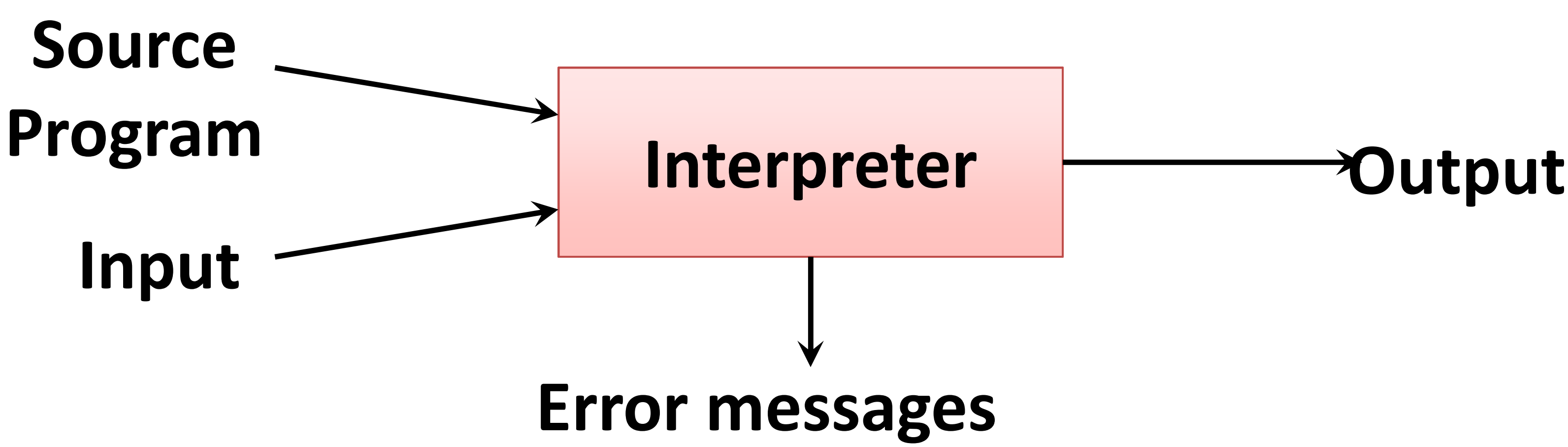
Compilers and Interpreters

- *"Compilation"*
  - Translation of a program written in a source language into a semantically equivalent program written in a target language



Compilers and Interpreters (cont'd)

- *"Interpretation"*
  - Performing the operations implied by the source program



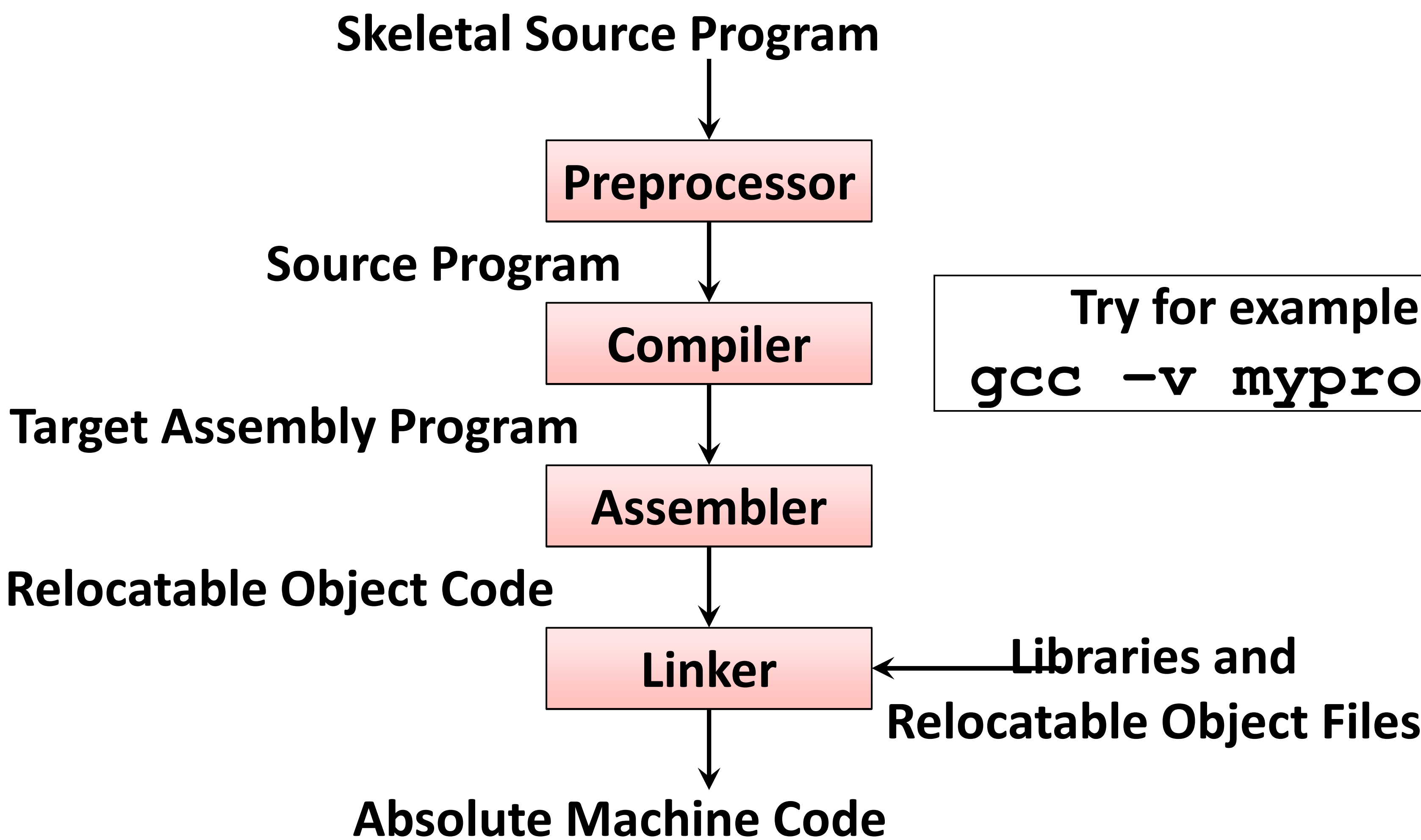
The Analysis-Synthesis Model of Compilation

- There are two parts to compilation:
  - *Analysis* determines the operations implied by the source program which are recorded in a tree structure
  - *Synthesis* takes the tree structure and translates the operations therein into the target program

Other Tools that Use the Analysis-Synthesis Model

- Editors (syntax highlighting)
- Pretty printers (e.g. doxygen)
- Static checkers (e.g. lint and splint)
- Interpreters
- Text formatters (e.g. TeX and LaTeX)
- Silicon compilers (e.g. VHDL)
- Query interpreters/compilers (Databases)

Preprocessors, Compilers, Assemblers, and Linkers



Try for example:

```
gcc -v myprog.c
```

RISC vs CISC

- RISC : arithmetic and memory instruction are well separated
- RISC : All instruction have same size
- RISC: Less number of Addressing mode
- RISC : Less number of type of instruction

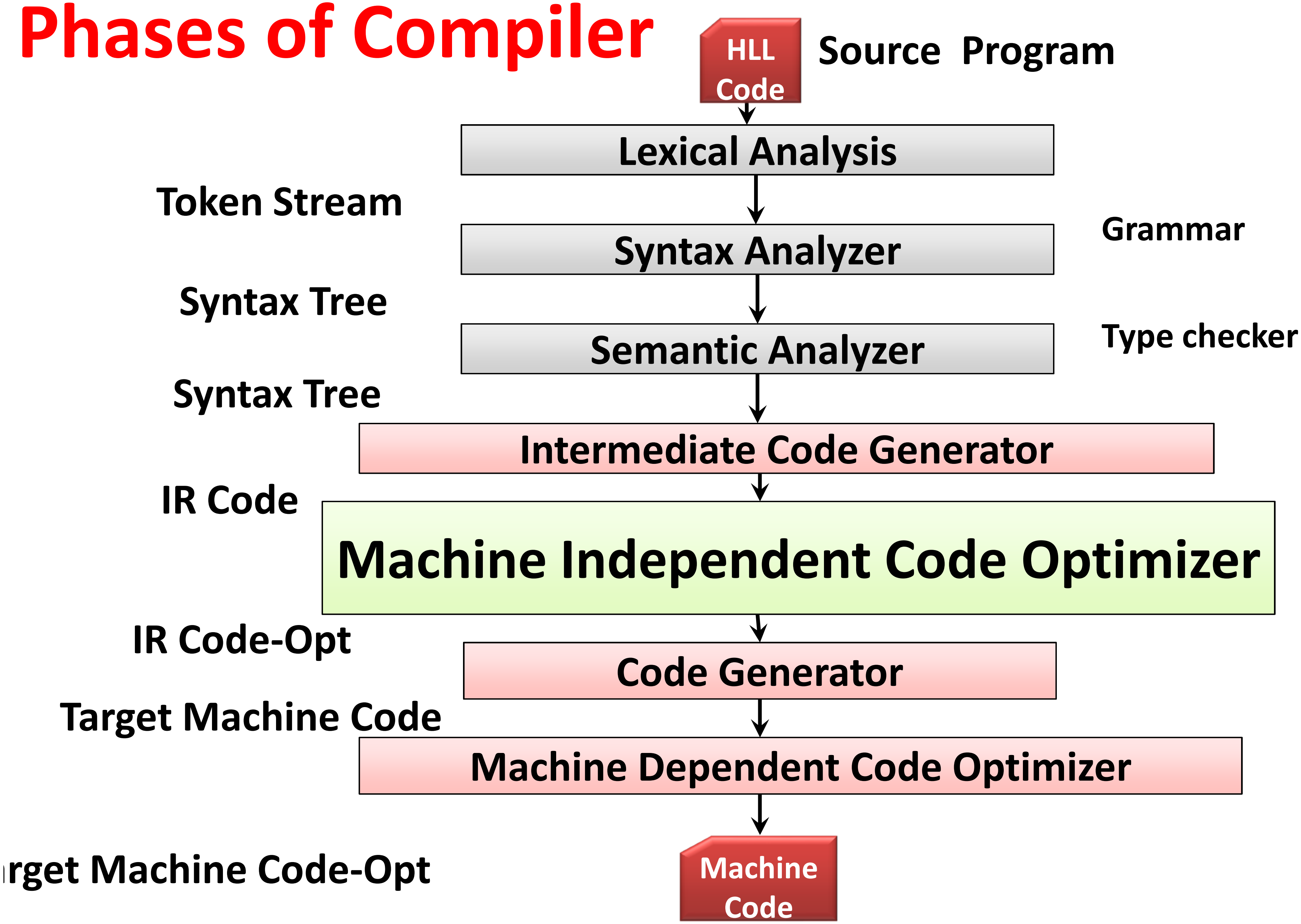
➔
  - Simple/less power/less area controller
  - Pipeline able design for RISC
  - Example of RISC: ARM (M1 from Apple, SD, MT), MIPS, PowePC
- *Example of CISC : X86/x86-64, VxWorks*
  - *CISC use micro-code to convert complex INS to simple INS*

GCC Options

- $gcc -E test.c   // Pre-process file
- $gcc –save-temps t.c

  //save Preprocess file (t.i), t.s (assmly), t.o

Phases of Compiler



The Phases of a Compiler

Phase	Output	Sample
Programmer	Source string	`A=B+C;`
Scanner (performs *lexical analysis*)	Token string	`'A', '=', 'B', '+', 'C', ';'` And *symbol table* for identifiers

Parser (performs *syntax analysis* based on the grammar of the programming language)	Parse tree or abstract syntax tree	`  ;`
		`  |`
		`  =`
		` / \`
		`A   +`
		`   / \`
		`  B   C`

Semantic analyzer (type checking, etc)	Parse tree or abstract syntax tree	

Intermediate code generator	Three-address code, quads, or RTL	`int2fp B       t1`
		`+      t1   C  t2`
		`:=     t2      A`

Optimizer	Three-address code, quads, or RTL	`int2fp B         t1` `+      t1  #2.3  A`

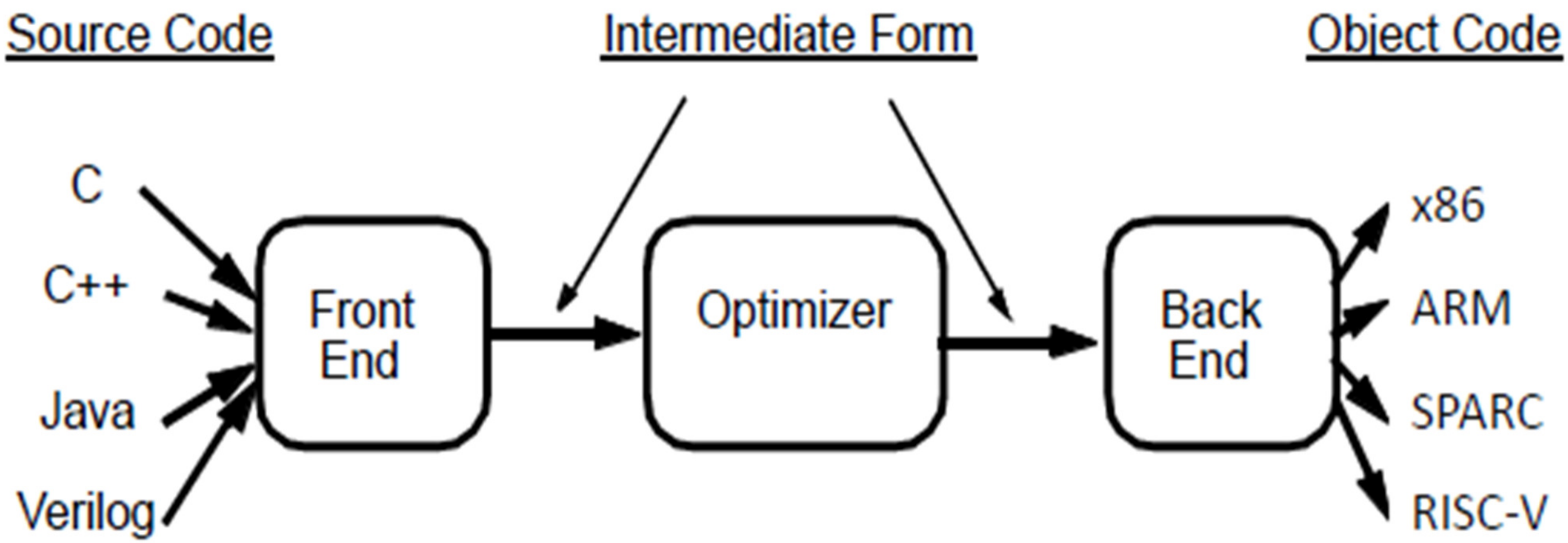
Code generator	Assembly code	`MOVF  #2.3,r1`
		`ADDF2 r1,r2`
		`MOVF  r2,A`

Peephole optimizer	Assembly code	`ADDF2 #2.3,r2` `MOVF  r2,A`

Grouping of Phases

- Compiler front and back ends:
  - Analysis (*machine independent* front end)
  - Synthesis (*machine dependent* back end)
- Passes
  - A collection of phases may be repeated only once (*single pass*) or multiple times (*multi pass*)
  - Single pass: usually requires everything to be defined before being used in source program
  - Multi pass: compiler may have to keep entire program representation in memory

Structure of a Compiler



- Optimizations are performed on an "intermediate form "
  - similar to a generic RISC instruction set
- Enables easy portability to multiple source languages, target machines

General GCC Optimization Options

- GCC optimization : - O0, - O1, -O2, -O3
- $man gcc
- At – O0 level:
  - Compiler refrain from most of the opt.
  - It is correct choice for analyzing the code with debugger
- At high level
  - Mixed up source lines, eliminate redundant variable, rearrange arithmetic expressions
  - Debugger has a hard time to give user a consistent view on code and data

General GCC Optimization Options

- Level 1
  - -fauto-inc-dec, -fmove-loop-invarient, -fmerge-constants, -ftree-copy-prop, -finline-fun-called-once
- Level 2
  - -falign-functions, -falign-loops, level, -finlining-small-fun, -finling-indirect-fun, -freorder-fun, -fstrict-aliasing
- Level 3
  - -ftree-slp-vectorize, -fvect-cost-model

CS536 Course Flow

- Intermediate Representation
- IR Code Generation
- Runtime Environment
- Code Generation: Basic Block, SSA, Reg. Alloc.
- **Machine In/Dependent Code Optimization**
- **Optimization for ILP**
- **Opt. for Parallelism (TLP) and Cache Locality**
- Inter procedural Analysis

Motivation 1: Optimizing Compilers for High Level Prog. Language

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;
          }
     }
}
```

Code generated by front end

```
     i := n-2
s5:  if i<0 goto s1
     j := 0
s4:  if j>i goto s2
     t1 = 4*j
     t2 = &A
     t3 = t2+t1
     t4 = *t3          ;A[j]
     t5 = j+1
     t6 = 4*t5
     t7 = &A
     t8 = t7+t6
     t9 = *t8         ;A[j+1]
     if t4 <= t9 goto s3
     t10 = 4*j
     t11 = &A
     t12 = t11+t10
     temp = *t12    ;temp=A[j]
```

```
     t13 = j+1
     t14 = 4*t13
     t15 = &A
     t16 = t15+t14
     t17 = *t16       ;A[j+1]
     t18 = 4*j
     t19 = &A
     t20 = t19+t18  ;&A[j]
    *t20 = t17        ;A[j]=A[j+1]
     t21 = j+1
     t22 = 4*t21
     t23 = &A
     t24 = t23+t22
    *t24 = temp       ;A[j+1]=temp
s3:  j = j+1
     goto S4
s2:  i = i-1
     goto s5
s1:
```

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

After optimization

Result of applying:

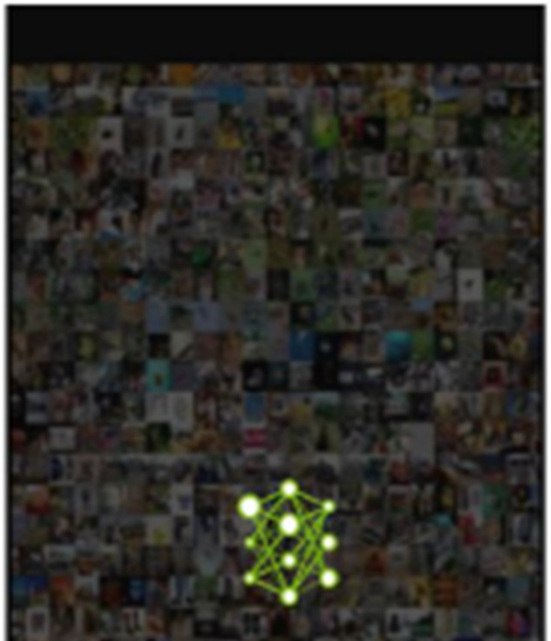
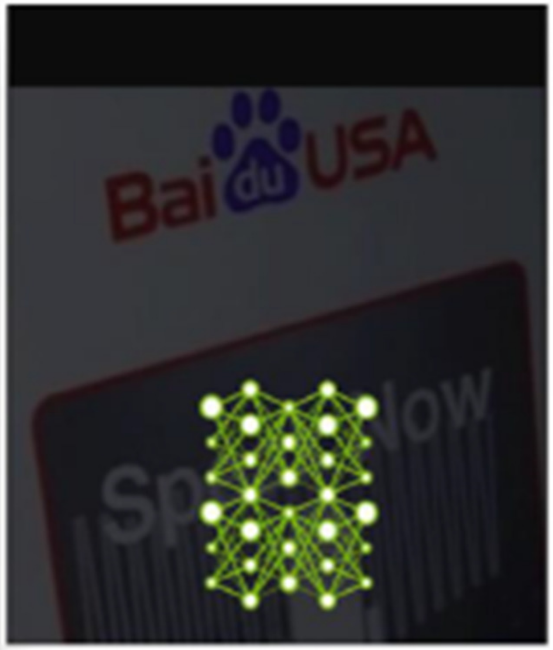
- global common subexpression
- loop invariant code motion
- induction variable elimination
- dead-code elimination

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:
```

Motiv2: High Perf. Machine Learning

7 ExaFLOPS 60 Million Parameters	20 ExaFLOPS 300 Million Parameters	100 ExaFLOPS 8700 Million Parameters
		
2015	2016	2017
Microsoft ResNet Superhuman Image Recognition	Baidu Deep Speech 2 Superhuman Voice Recognition	Google Neural Machine Translation Near Human Language Translation

1 ExaFLOPS = 10^{18} FLOPS

Motiv2:Nvidia Hopper GPU Arch

80B transistors
900 mm2
1650 MHz

132 Streaming Multiprocessors (SM)
528 Tensor cores
16,896 CUDA cores

Each SM

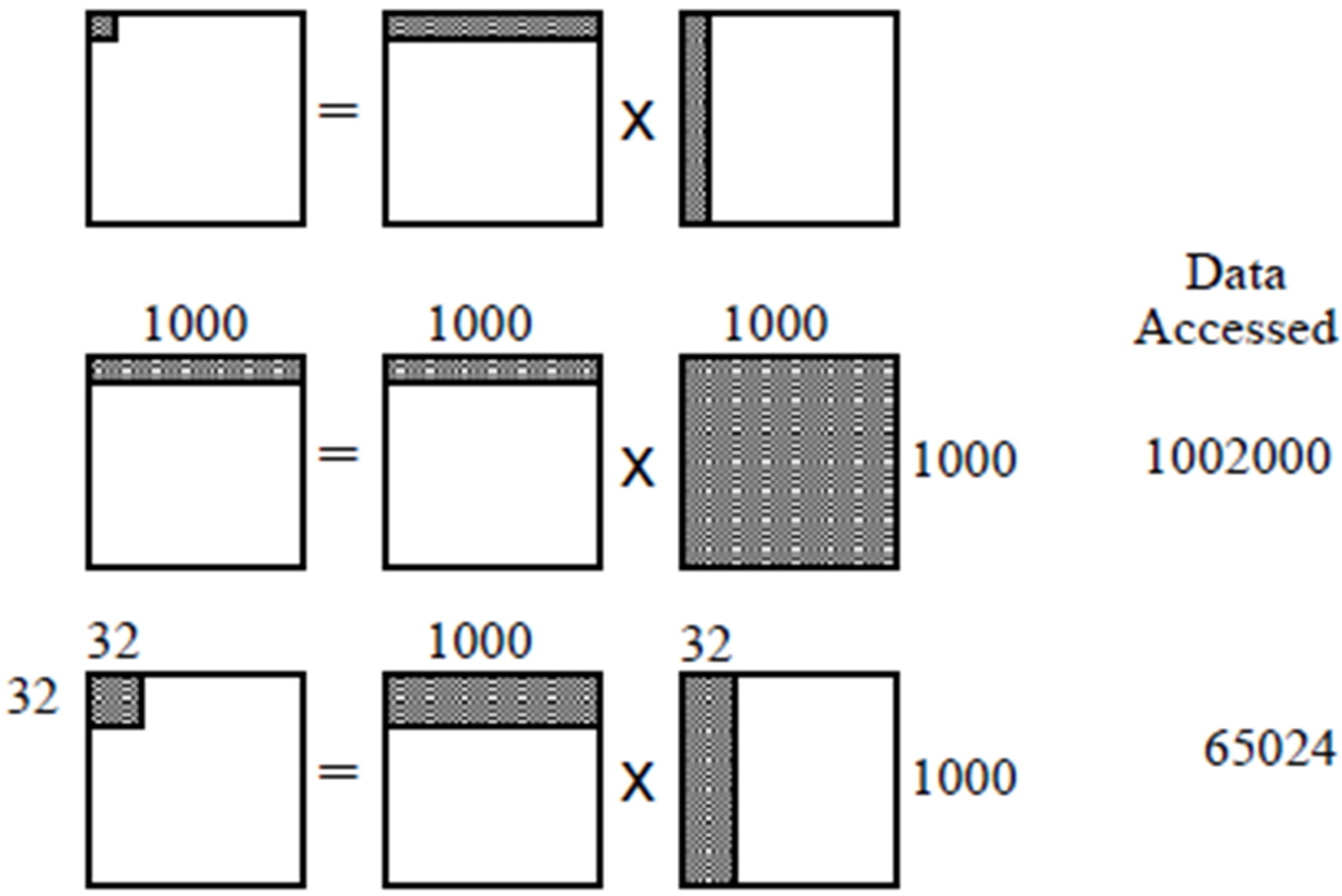
128 FP32 cores
128 Int cores
64 FP64 cores

4 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

FP64: 30 TFLOPS
FP32: 500 TFLOPS
FP16: 1000 TFLOPS
FP8/INT8 Tensor: 2000 TFLOPS

Blocking for Matrix Multiplication



Blocking for Matmul: Original Code

```
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];
      }
   }
}
```

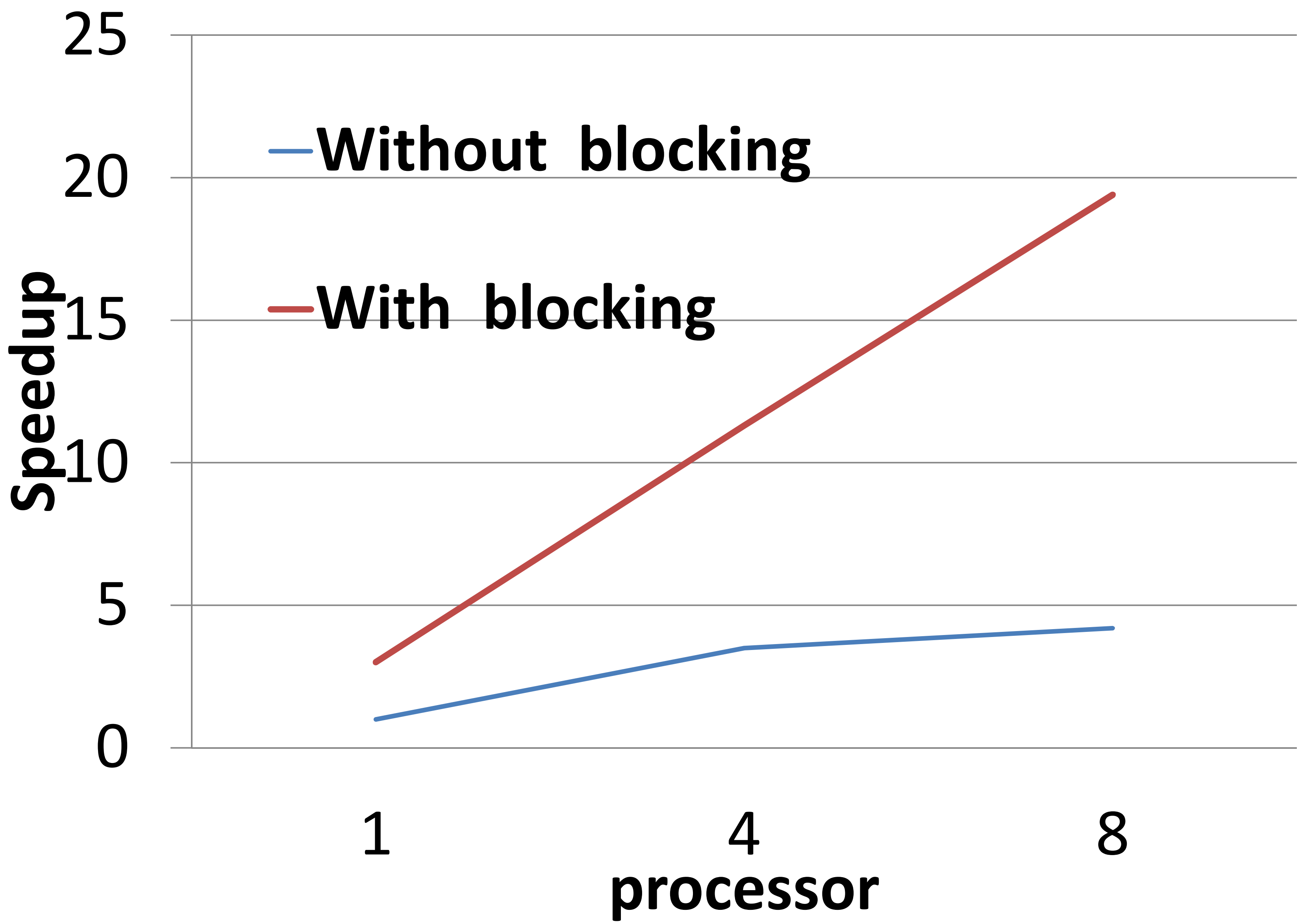
Blocking for Matmul: Stripmine 2 outerloop

```
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];
}}}}}
```

Blocking for Matmul: permute

```
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];
}}}}}
```

Blocking for Matmul :Impact



Thanks