ECE 454
Computer Systems Programming

Compiler Optimizations

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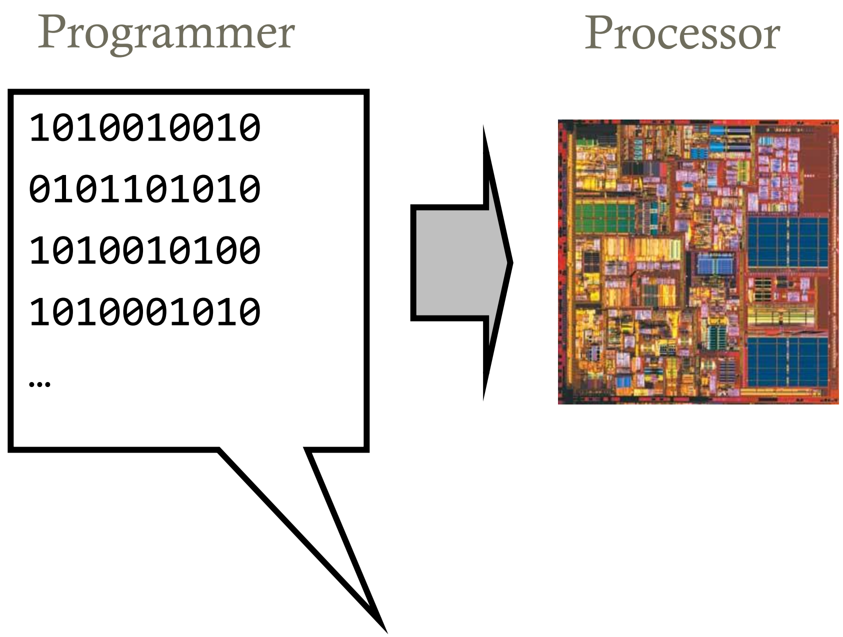
Content

- History and overview of compilers
- Basic compiler optimizations
- Program optimizations
- Advanced optimizations
  - Parallel unrolling
  - Profile-directed feedback

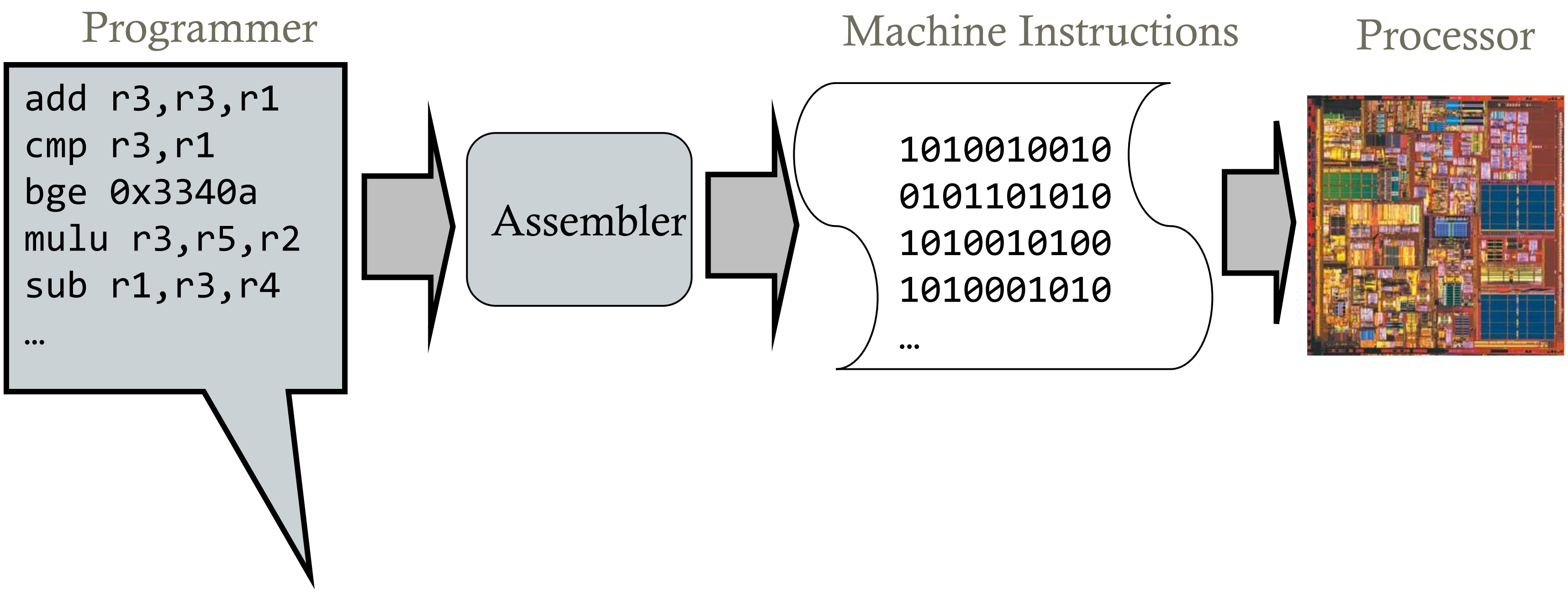
A Brief History of Compilation

In the Beginning…



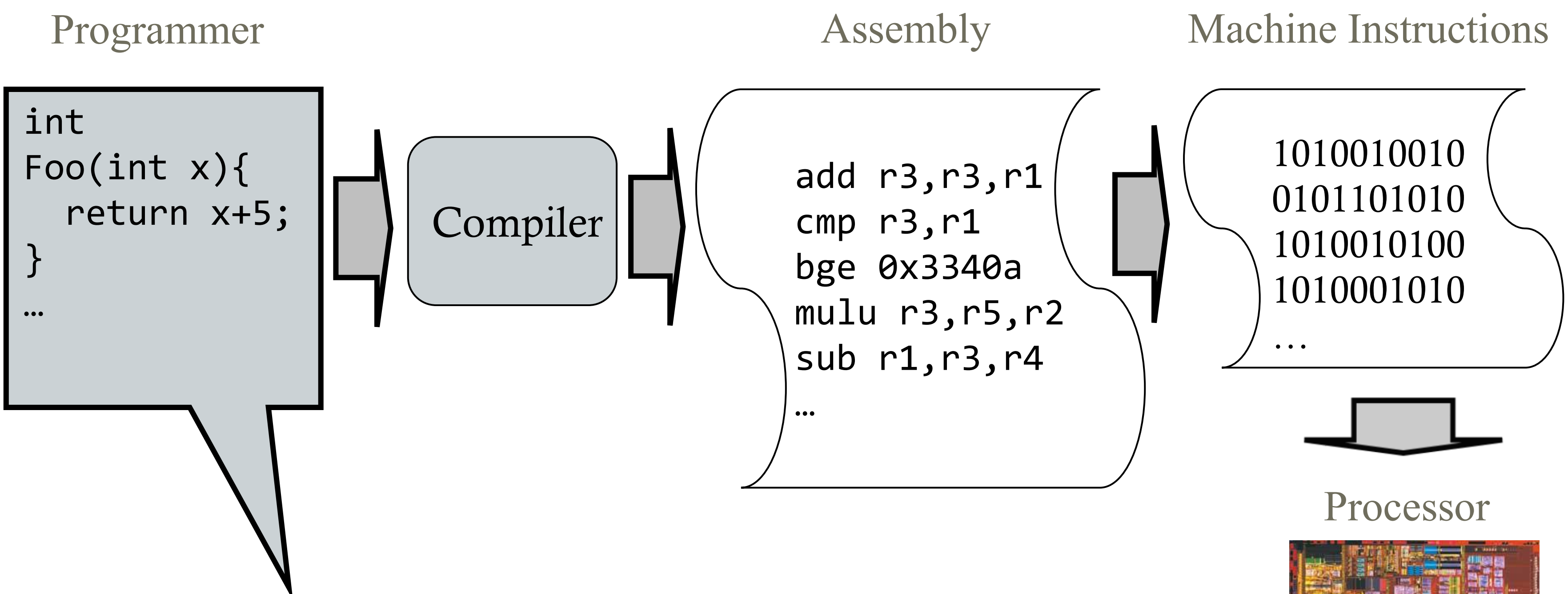
☞Programmers wrote machine instructions

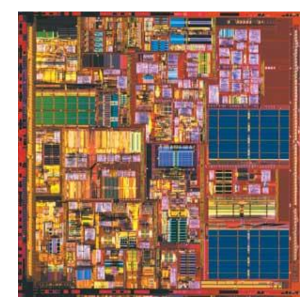
Then Came the Assembler



☞Programmers wrote human-readable assembly

Then Came the Compiler





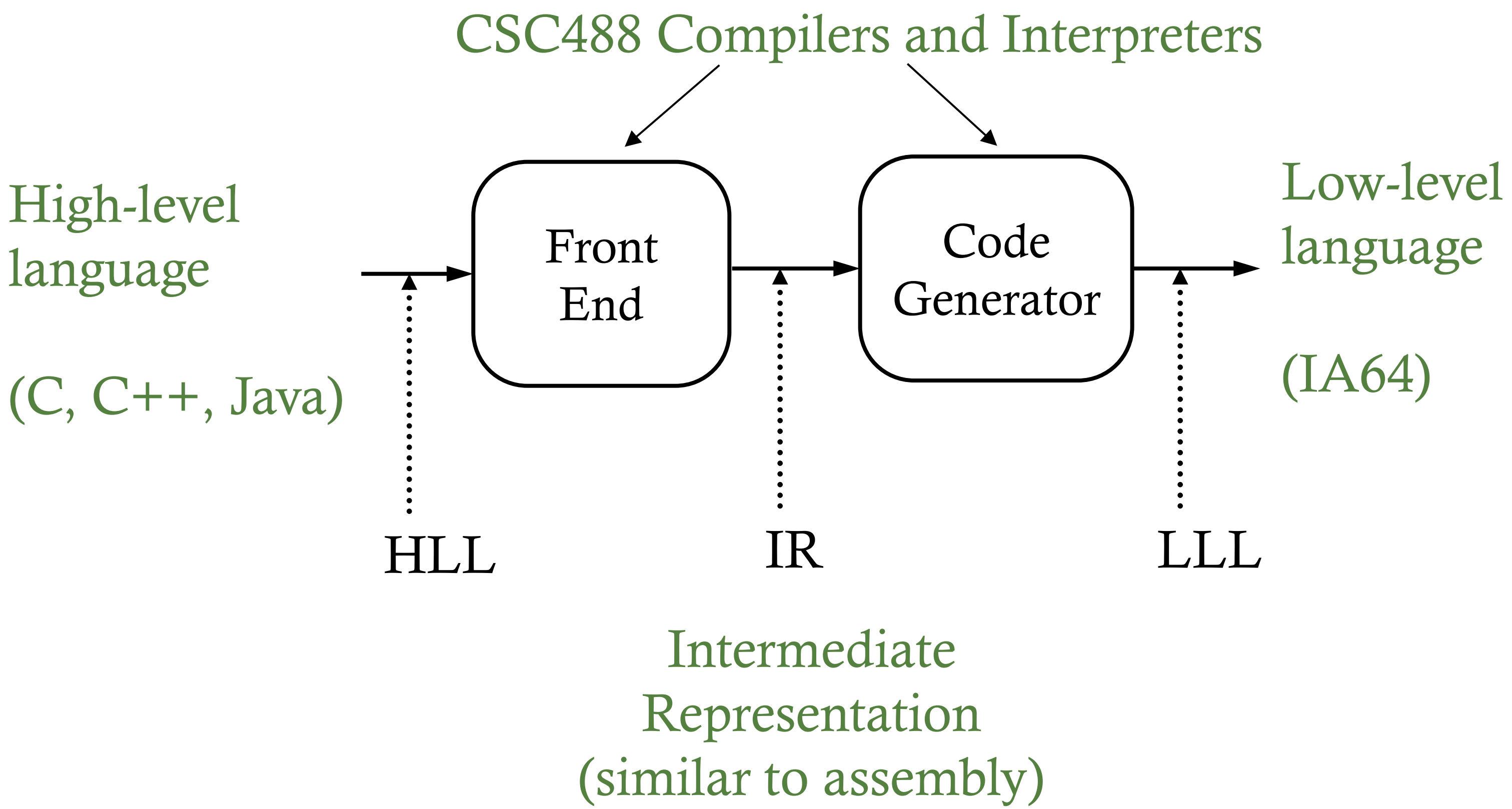
☞ Programmers wrote high-level language (HLL)

Overview of Compilers

Goals of a Compiler

- Correct program executes correctly
- Provide support for debugging incorrect programs
- Program executes fast
- Compilation is fast?
- Small code size?
- More energy efficient program?

Inside a Basic Compiler

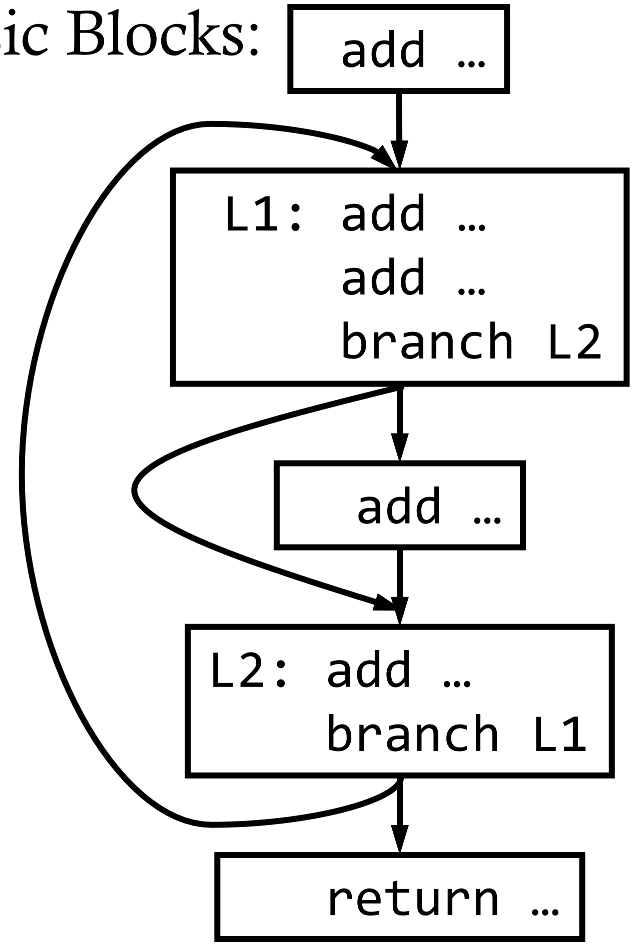


Control Flow Graph:
(how a compiler sees your program)

Example IR:

```
     add …
L1:  add …
     add …
     branch L2
     add …
L2:  add …
     branch L1
     return …
```

Basic Blocks:



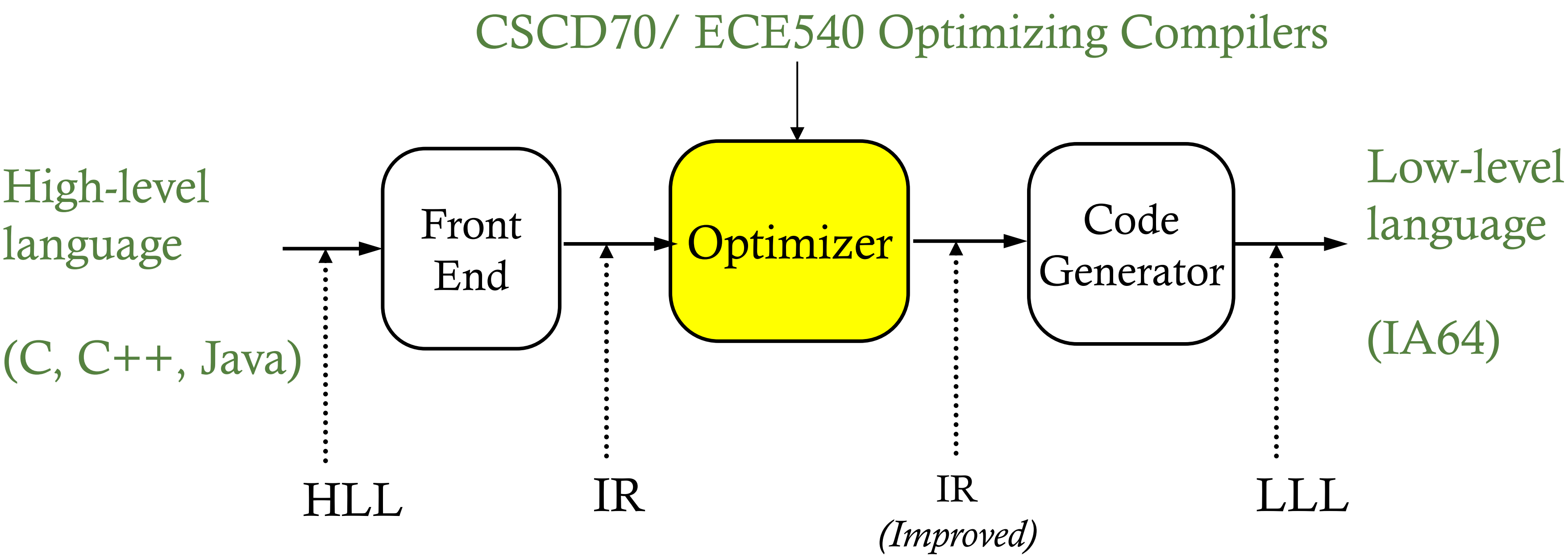
Basic Block: a group of consecutive instructions with a single entry point and a single exit point

Data Flow Analysis

- Many compiler optimizations (discussed later) use a technique called data flow analysis
- Basic idea
  - Analyse and summarize the effects of instructions in a basic block
  - Use CFG to propagate these effects to succeeding basic blocks
- E.g., reaching definition data flow analysis
  - Calculates for each program point the set of definitions (program points) that may potentially reach this program point

```
1:if b==4 then          // BB1
2:    a = 5;            // BB2
3:else
4:    a = 3;            // BB3
5:endif
6:if a < 4 then ...     // BB4
```

Inside an Optimizing Compiler



Performance Optimization: 3 Requirements

- Preserve correctness
  - The speed of an incorrect program is irrelevant
- Improve performance of average case
  - Optimized program may be worse than original if unlucky
- Be "worth the effort"
  - Is this example worth it?
    - 1 person-year of work to implement compiler optimization
    - 2x increase in compilation time
    - 0.1% improvement in speed

How do Optimizations Improve Performance?

- Recall

```
Execution_time = num_instructions * CPI * time/cycle
```

- Fewer instructions
  - Use optimized sequence of instructions
  - Use new instructions
- Fewer cycles per instruction
  - Schedule instructions to avoid hazards
  - Improve cache/memory behavior
    - E.g., prefetching, code and data locality

Role of Optimizing Compilers

- Provide efficient mapping of program to machine instructions
  - Eliminate minor inefficiencies
  - Register allocation
  - Instruction selection
  - Instruction scheduling

- Don't (usually) improve asymptotic efficiency
  - Up to programmer to select best overall algorithm
  - Big-O savings are (often) more important than constant factors
    - But constant factors also matter

Limitations of Optimizing Compilers

- Operate under fundamental constraints
  - Must not cause any change in program behavior under any possible condition
- Most analysis is performed only within procedures
  - Inter-procedural analysis is too expensive in most cases
- Most analysis is based only on static information
  - Compiler has difficulty anticipating run-time inputs
- When in doubt, the compiler must always be conservative

Role of the Programmer

- How should I write my programs, given that I have a good, optimizing compiler?
- Don't: smash code into oblivion
  - Hard to read, maintain, assure correctness

Role of the Programmer

- How should I write my programs, given that I have a good, optimizing compiler?
- Do:
  - Select best algorithm
  - Write code that's readable and maintainable
    - Procedures, recursion
    - Even though these may slow down code
  - Focus on inner loops
    - Do detailed optimizations where code will be executed repeatedly
    - Will get most performance gain here
  - Eliminate optimization blockers
    - Allows compiler to do its job!

Basic Compiler Optimizations

Compiler Optimizations

- Machine independent (apply equally well to most CPUs)
  - Constant propagation
  - Constant folding
  - Copy propagation
  - Common subexpression elimination
  - Dead code elimination
  - Loop invariant code motion
  - Function inlining

Compiler Optimizations

- Machine dependent (apply differently to different CPUs)
  - Instruction selection and scheduling
  - Loop unrolling
  - Parallel unrolling
- Possible to do all these optimizations manually, but much better if compiler does them
  - Many optimizations make code less readable/maintainable

Constant Propagation (CP)

- Replace variables with constants when possible

```
a = 5;
b = 3;
    :
    :
n = a + b;
for (i = 0 ; i < n ; ++i) {
        :
}
```

```
n = 5 + 3
```

Constant Folding (CF)

- Evaluate expressions containing constants

```
    :
    :
    :
    :
n = 5 + 3;
for (i = 0 ; i < n ; ++i) {
      :
}
```

n = 8

8

- Can lead to further optimization
  - E.g., another round of constant propagation

Common Sub-Expression Elimination (CSE)

- Try to only compute a given expression once

```
a = c * d;                    ⇒        a = c * d;
      :                                       :
      :                                       :
d = (c * d + t) * u                    d = (a + t) * u
```

- Need to ensure the variables have not been modified

Copy Propagation

- Replace target of assignment with corresponding value

:
:
:
:

~~y = x;~~

z = 3 + ~~y~~;

x

- Often used after common sub-expression elimination and other optimizations

Dead Code Elimination (DCE)

- Compiler can determine if certain code will never execute

```
debug = 0;  // set to false                  debug = 0;
     :
if (debug) {
     :
                                    ⇒
     :
}
a = f(b);                                    a = f(b);
```

- Compiler will remove that code
  - You don't have to worry about such code impacting performance
  - Makes it easier to have readable/debugable programs

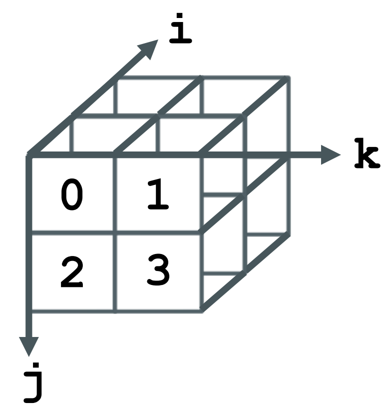
Loop Invariant Code Motion (LICM)

- Loop invariant: value does not change across iterations
- LICM: moves invariant code out of the loop
- Leads to significant performance win

Loop Invariant Code Motion (LICM)

- Consider this triply nested loop

```
for (i=0; i < I;  ++i) {
  for (j=0; j < J; ++j) {
    for (k=0 ; k < K; ++k) {
      a[i][j][k] = i*j*k;
    }
  }
}
```



- In C, a multi-dimensional array is stored in row-major order

a[0][0][0]	a[0][0][1]	…	a[0][0][K-1]	a[0][1][0]	…	a[I-1][J-1][0]	..	a[I-1][J-1][K-1]

```
char a[I][J][K];

addr of a[i][j][k] = (addr of a) + (i x J x K) + (j x K) + (k)
```

Loop Invariant Code Motion (LICM)

```
addr of a[i][j][k] = (addr of a) + (i x J x K) + (j x K) + (k)
```

```
for (i=0; i < I;  ++i) {
  for (j=0; j < J; ++j) {
    for (k=0 ; k < K; ++k) {
      a[i][j][k] = i*j*k;
    }
  }
}
```

⇒

```
for (i = 0; i < I; ++i) {
  t1 = a + i * J * K; // t1=a[i];
  for (j = 0; j < J; ++j) {
    t2 = t1 + j * K; // t2=t1[j];
    for (k = 0 ; k < K; ++k) {
      t2[k] = i * j * k;
    }
  }
}
```

Loop Invariant Code Motion (LICM)

```
addr of a[i][j][k] = (addr of a) + (i x J x K) + (j x K) + (k)
```

```
for (i=0; i < I;  ++i) {
  for (j=0; j < J; ++j) {
    for (k=0 ; k < K; ++k) {
      a[i][j][k] = i*j*k;
    }
  }
}
```

⇒

```
for (i = 0; i < I; ++i) {
  t1 = a + i * J * K; // t1=a[i];
  for (j = 0; j < J; ++j) {
    t2 = t1 + j * K; // t2=t1[j];
    tmp = i * j;
    for (k = 0 ; k < K; ++k) {
      t2[k] = tmp * k;
    }
  }
}
```

- When I=J=K=100, inner loop will execute 1,000,000 times
  - Many of the computations in the inner loop are moved out
  - Improves performance dramatically

Function Inlining

- A function call site is replaced with the body of the function

```
foo(int z){
  int m = 5;
  return z + m;
}

main(){
  …
  x = foo(x);
  …
}
```

```
main(){
 …
 {
  int foo_z = x;
  int foo_m = 5;
  int foo_return = foo_z + foo_m;
  x = foo_return;
 }
 …
}
```

```
main(){
  …
  x = x + 5;
  …
}
```

Function Inlining

- Performance
  - Eliminates call/return overhead
  - Can expose potential optimizations
  - Can be hard on instruction-cache if many copies made
    - Code size can increase if large procedure body and many calls
- As a programmer
  - A good compiler should inline for best performance
  - Feel free to use procedure calls to make your code readable!

Loop Unrolling

```
j = 0;
while (j < 100){
   a[j] = b[j+1];
   j += 1;
}
```

```
j = 0;
while (j < 99){
   a[j] = b[j+1];
   a[j+1] = b[j+2];
   j += 2;
}
```

- Reduces loop overhead, why?
  - Fewer adds to update j
  - Fewer loop condition tests
  - Reduces branch penalties
- Enables more aggressive instruction scheduling
  - I.e., more instructions in loop basic block for scheduler to move around

Summary: gcc Optimization Levels

- -g: Include debug information, no optimization
- -O0: Default, no optimization
- -O1: Do optimizations that don’t take too long
  - CP, CF, CSE, DCE, LICM, inline functions called once
- -O2: Take longer optimizing, more aggressive scheduling
  - E.g., inline small functions
- -O3: Make space/speed trade-offs
  - Can increase code size, loop unrolling, more inlining
- -Os: Optimize program size