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Compiler Construction

Lecture 16: Introduction to optimizations

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Overview

- Optimizations
  - Definition, objectives, location in the compiler tool flow
  - Obtaining and applying evaluation criteria
  - Common vs. worst case
  - Optimization properties

Optimization

- What do we mean when we talk about an **optimizing** compiler?

- ***Mathematical*** optimization is the selection of a best element (with regard to some criterion) from some set of available alternatives

- With software, it is often hard to find a real optimum
    - Compiler "optimizations’ **try** to minimize or maximize some attributes of an executable program
    - Large search space makes finding the real optimum impossible in many cases
    - In general, optimization is undecidable, often NP-complete
- Nevertheless, we will continue using the term "optimizations" here

Why optimization?

- To help programmers…
  - They (try to…) write modular, clean, high-level programs
- Compiler generates efficient, high-performance assembly
  - Programmers don't write optimal code
- High-level languages make avoiding redundant computation inconvenient or impossible
  - e.g. `A[i][j] = A[i][j] + 1`
- Architectural independence
  - Optimal code depends on features not expressed to the programmer
  - Modern architectures assume optimization
- Important: **Ensure safety of optimizations**
  - Optimizations may never change the meaning (semantics) of a program!

Why optimization?

Code generated from simple AST traversal (+IR transformation) is often quite inefficient

```c
int foo(int w) {
  int x, y, z;
  x = 3 + 5;
  y = x * w;
  z = y - 0;
  return z * 4;
}
```

gcc -O0

```
        .globl _foo
_foo:
LFB0:
        pushq   %rbp
LCFI0:
        movq    %rsp, %rbp
LCFI1:
        movl    %edi, -20(%rbp)
        movl    $8, -4(%rbp)
        movl    -4(%rbp), %eax
        imull   -20(%rbp), %eax
        movl    %eax, -8(%rbp)
        movl    -8(%rbp), %eax
        movl    %eax, -12(%rbp)
        movl    -12(%rbp), %eax
        sall    $2, %eax
        popq    %rbp
LCFI2:
        ret
```

gcc -O3

```
        .globl _foo
_foo:
LFB0:
        movl    %edi, %eax
        sall    $5, %eax
        ret
```

Optimization objectives

Which optimizations can a compiler try to achieve (examples)?

- Reduce **runtime** (in seconds)
- Reduce **code size** (in bytes)
- Reduce **power** consumption (in Watt)
- Reduce **energy** consumption (in Joule/Wh)
    - Objectives other than runtime relevant in embedded systems
- We also call all these objectives "**non-functional properties**"
    - They do not change the **semantics** of the code, but properties that influence its execution
- Code optimizations consist of two general stages:
    - **Analysis**: find optimization opportunities
    - **Transformation**: apply code changes

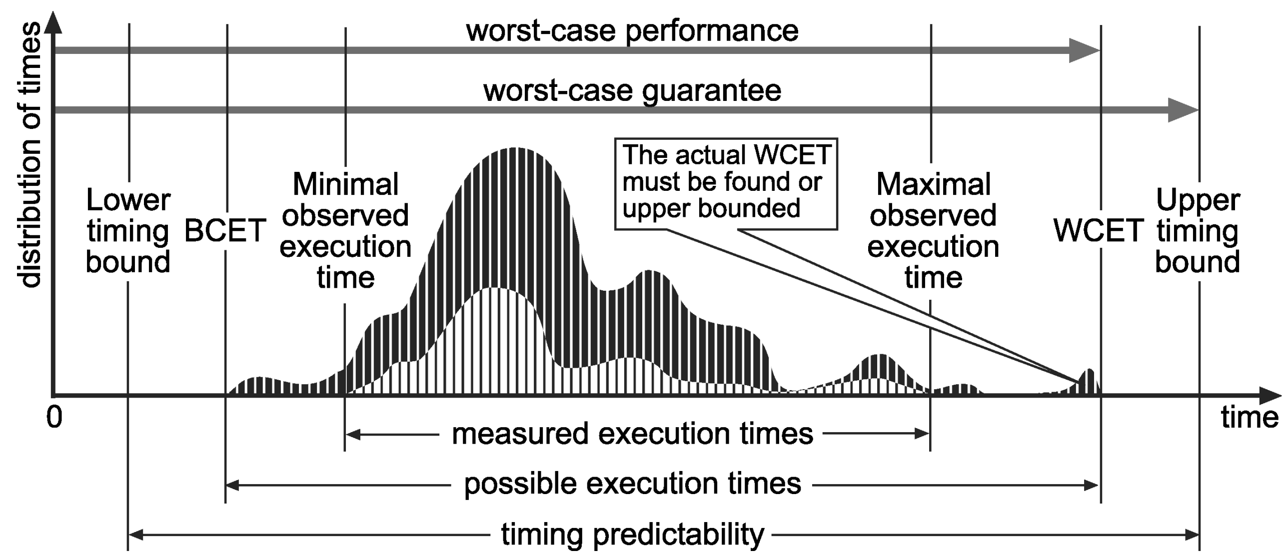
Optimizations… for what?

Most compiler optimizations consider the **common case**

- optimize cases providing largest benefit for the **average use case**

Some applications require optimization for the **worst case**

- in real-time systems, the **worst-case execution time** (WCET) determines if a system can operate safely under given real-time constraints
- a system that reacts too late can cause a catastrophe
- think of airbag controls in a car



[Wilhelm+08]

WCET: Worst-Case Execution Time
BCET: Best-Case Execution Time
ACET: Average-Case Execution Time

Optimizations become more difficult

Many architectural issues to think about

- Exploiting parallelism
    - instruction-level (ILP), thread, multi-core, accelerators
- Effective management of memory hierarchy
    - Registers [1], Caches (L1, L2, L3), Memory/NUMA, Disk
- Energy modes and heterogeneous multicores
    - Dynamic voltage-frequency scaling (DVFS), clock gating, big.LITTLE architectures

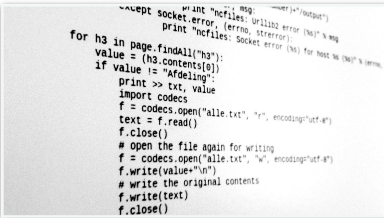
Small architectural changes have big impact – hard to reason about

Example

- Program optimised for CPU with Random cache replacement
- What do you change for new machine with LRU?

Where to apply optimizations

Source code



Lexical analysis → Syntax analysis → Semantic analysis → IR generation → ***IR*** → **IR optimization** (***IR***)

↓ ***machine code***

Code generation

↓ ***machine code***

Code optimization → machine-level program

machine-level program

Many analyses and transformations are general (not dependent on the target machine), so they can be easily applied on the **IR level**

Some analyses and optimizations are machine-dependent and better applied on the **machine code level**

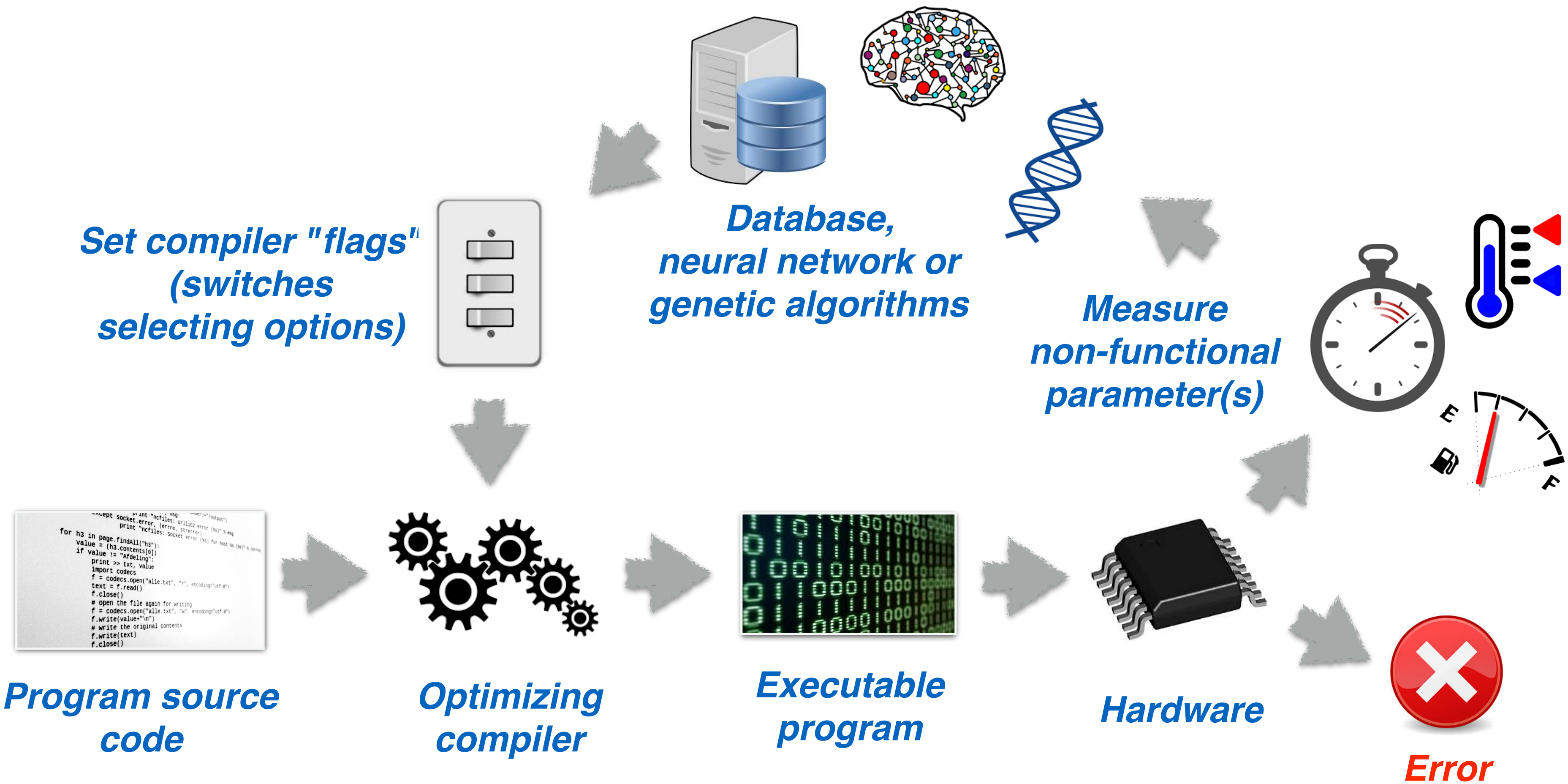
Optimization approaches

How can a compiler know that a **transformation** actually leads to an **optimization?**

- Simple approach: **hope for the best**
  - Example: "a lower number of instruction results in faster code"
  - This has worked surprisingly well for early architectures
- **Apply heuristics**
  - Used in many optimization decisions when concrete data or models are not available or search space too large
  - Examples:
    - Inlining decisions, Unrolling decisions, Packed-data (SIMD) optimization decisions, Instruction selection, Register allocation, Instruction scheduling, Software pipelining

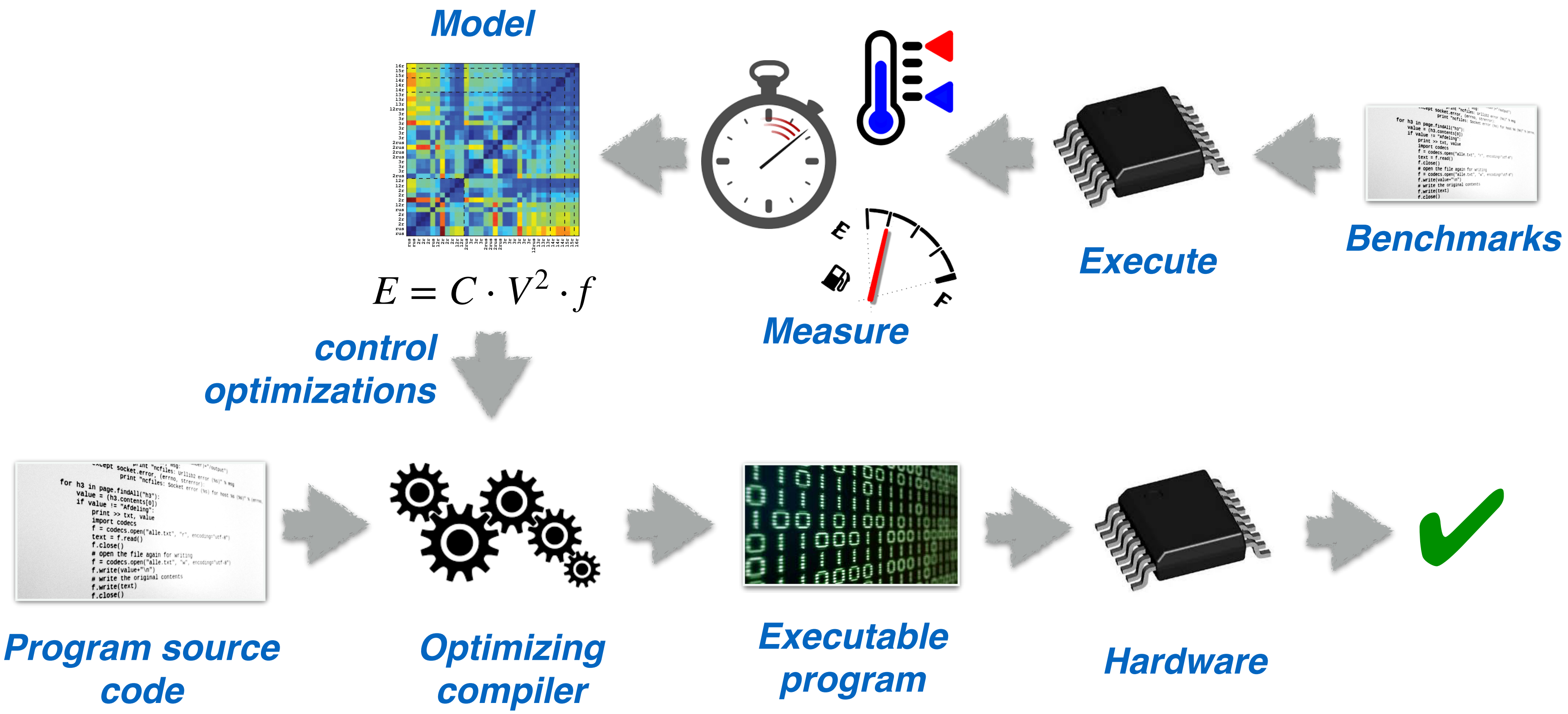
Optimization approaches

- Compile, run, measure, change options and repeat… [2,3]



Optimization approaches

- Integrate models of non-functional parameters into optimization decisions [4,5,6]



Example optimization: constant folding

Idea:

if operands are known at compile time, perform the operation **statically** (= once, during compilation)

```
int x = (2 + 3) * y → int x = 5 * y
b & false           → false
```

- What performance metric does it improve?
  - In general, the question whether an optimization improves performance is undecidable
- At which compilation step can it be applied?
  - Intermediate representation
  - After optimizations that create constant expressions

Example optimization: constant folding

```
int x = (2 + 3) * y → int x = 5 * y
```

- When is constant folding safely applicable?
  - for Boolean values: yes
  - for integer values: *almost always* yes
    - exception: division by zero
  - for floating point values: *caution*
    - e.g. rounding effects may lead to numerically different results
- General consideration of safety
  - Whether an optimization is safe depends on language semantics.
  - Languages that provide weaker guarantees to the programmer permit more optimizations, but have more ambiguity in their behavior – see e.g. [7]

Algebraic simplification

- More general form of constant folding
  - Makes use of mathematically sound simplification rules
- Identities:

```
a * 1     →  a
a + 0     →  a
b | false →  b
```

- Associativity and commutativity rules:

```
(a + b) + c →  a + (b + c)
a + b       →  b + a
```

Algebraic simplification

- Combined with constant folding:

```
(a + 1) + 2 → a + (1 + 2) → a + 3
(2 + a) + 4 → (a + 2) + 4 → a + (2 + 4) → a + 6
```

- Iteration of these optimizations is useful – but how much?

Strength reduction

- Replace expensive operation with cheaper one:

```
a * 4     →  a << 2
a * 7     →  (a << 3) - a
a / 64    →  (a >> 6)
```

Division by non-power of 2 integer constants is more complex, see [8], Ch. 10-4

- Effectiveness of this optimization depends on the architecture
  - Useful if fast shifter (barrel shifter) is available

```
int foo(int a) {
  int z;
  z = a*7;
  return z;
}
```

clang -O0

```
imull   $7, -4(%rbp), %edi
```

clang -O3

```
leal (,%rdi,8), %eax
subl %edi, %eax
```

What's next?

- Optimizations in detail: analyses and transformations

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