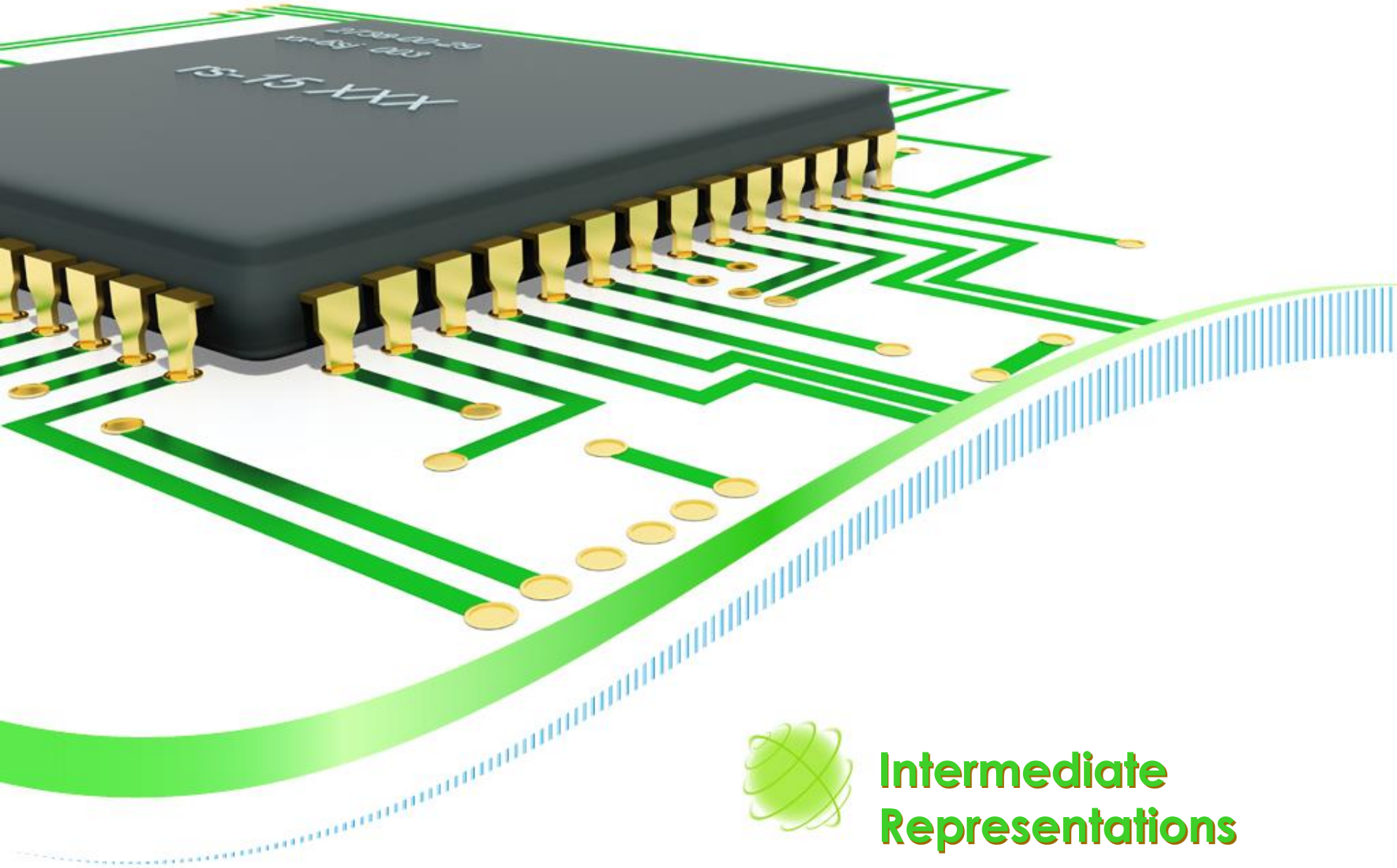
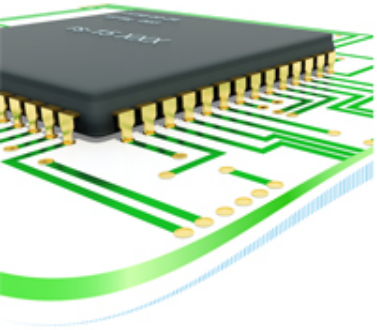


Intermediate Representations

Definition

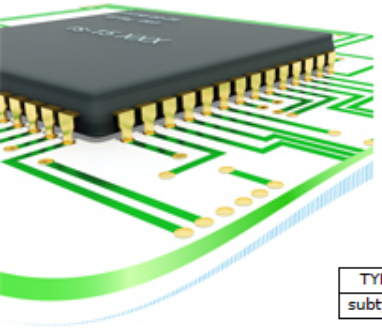


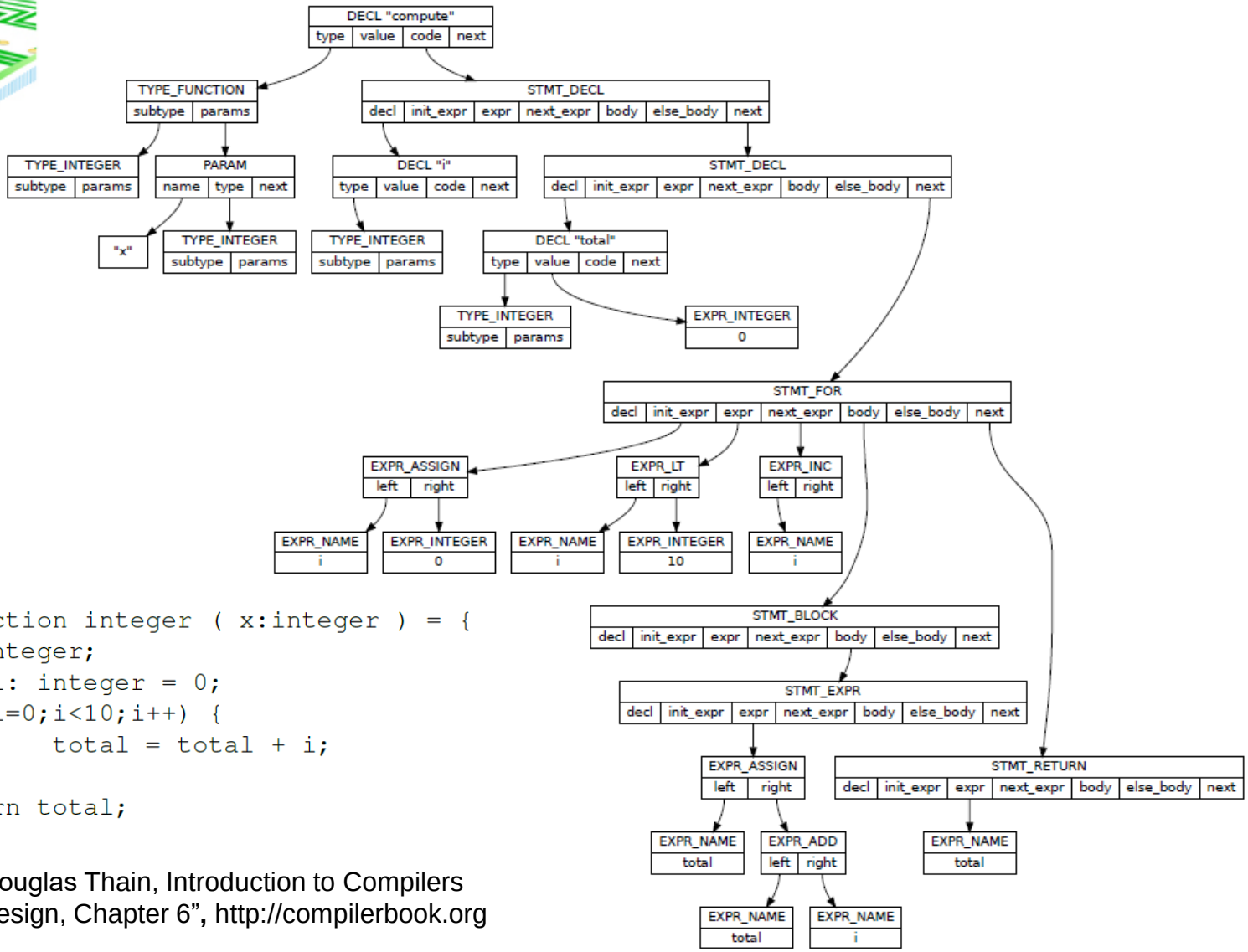
An intermediate representation is a composite derivative structure that supports generation of target code.

Extends the meaning,
regards the target architectures.

Abstract Syntax Tree (AST)

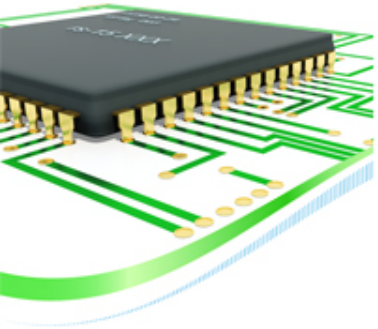
Semantic Representation as Graphical IR






```
compute: function integer ( x:integer ) = {
        i: integer;
        total: integer = 0;
        for(i=0;i<10;i++) {
                total = total + i;
        }
        return total;
}
```

Example from “Douglas Thain, Introduction to Compilers and Language Design, Chapter 6”, http://compilerbook.org

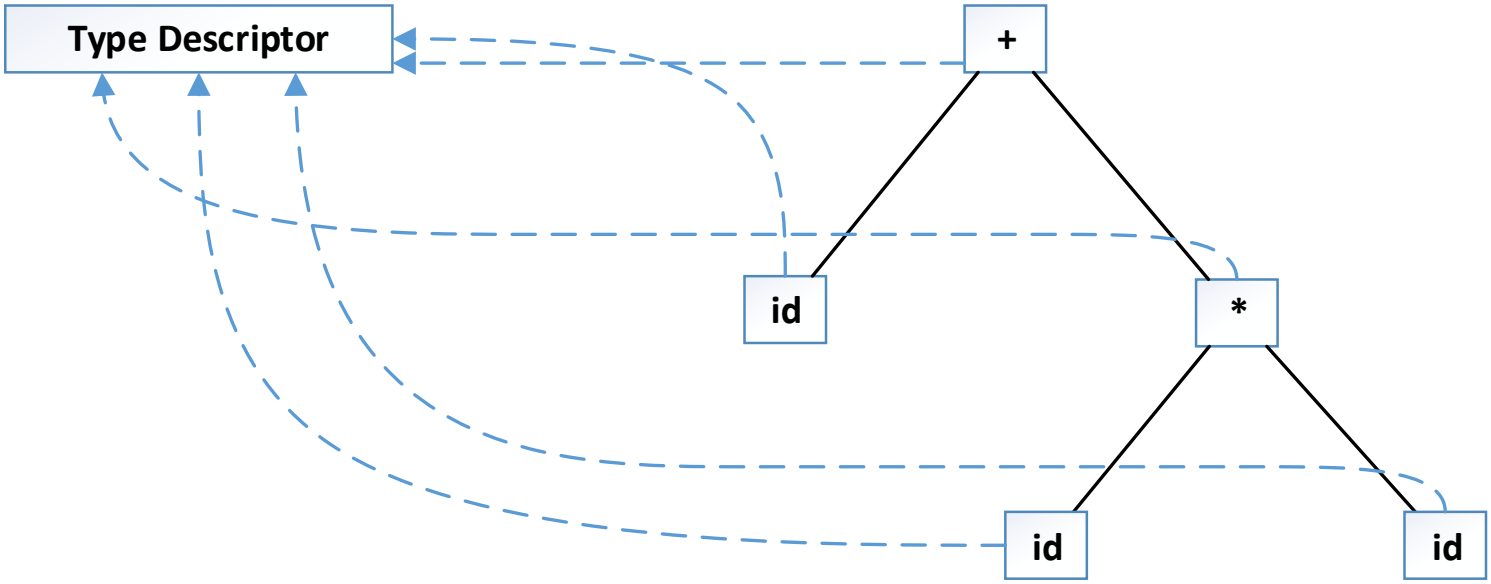


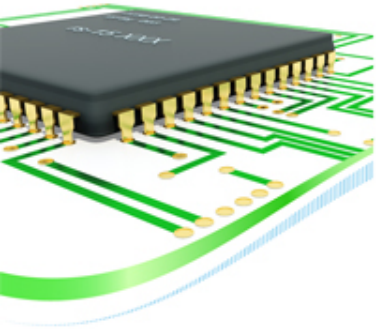
Abstract Syntax Tree (AST)

Semantic Representation as Graphical IR

Syntax is hierarchical. **Meaning is not!**

- **Expressions**
- **Structure – Member Relationships**
- **Flow Control Statements**
- **Other Declarations**
- **…**

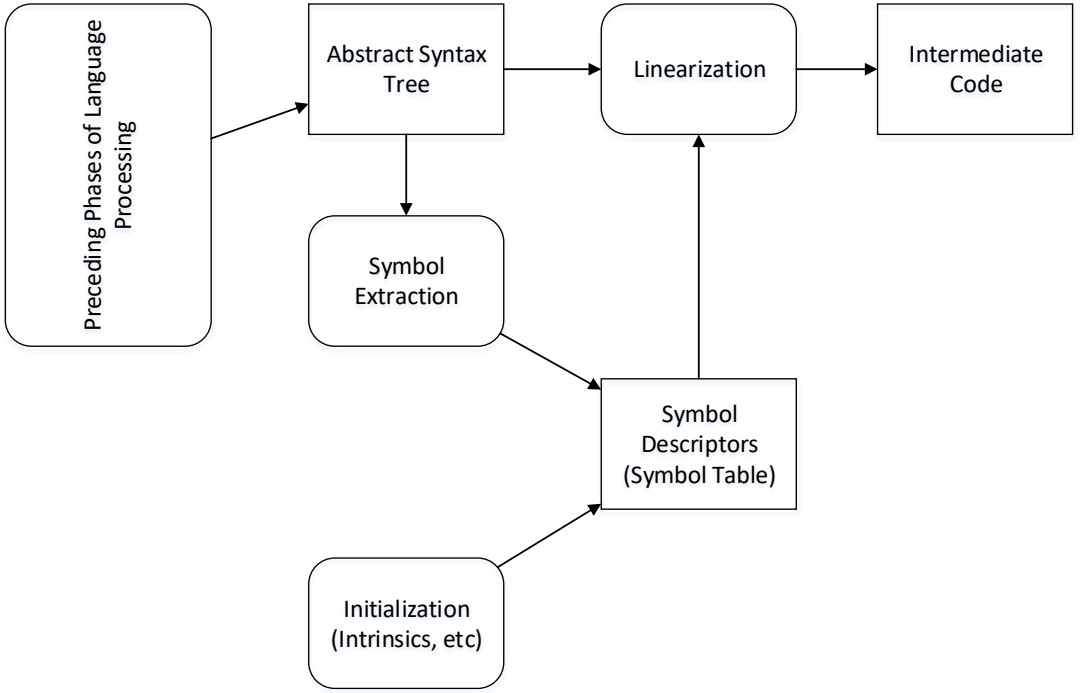




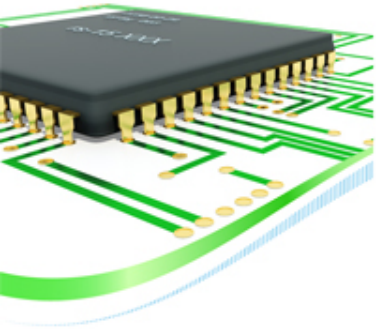
IR Generation

Linear Representations

Transforming into linear structure



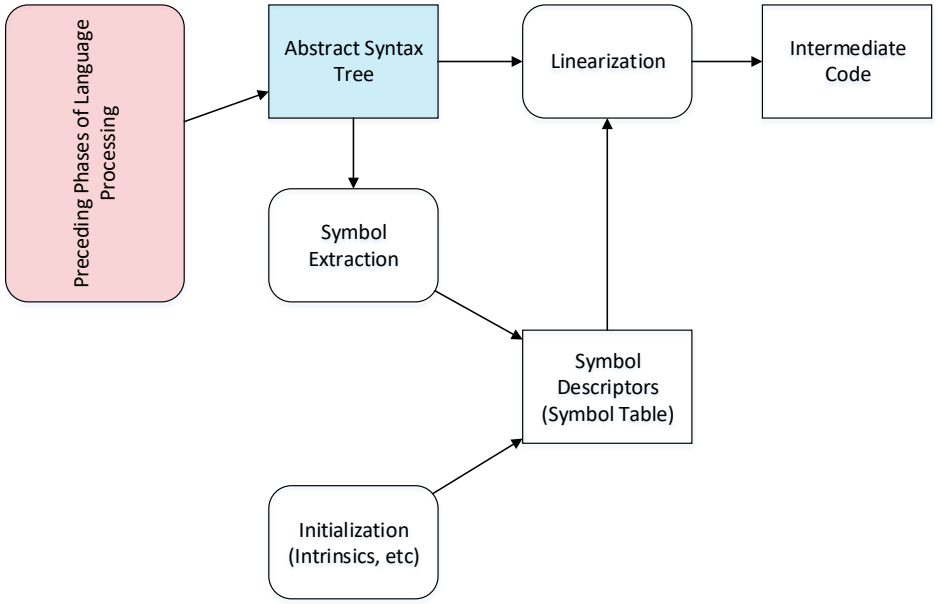
Just a scheme for transformation.



IR Generation

Graphical Representations

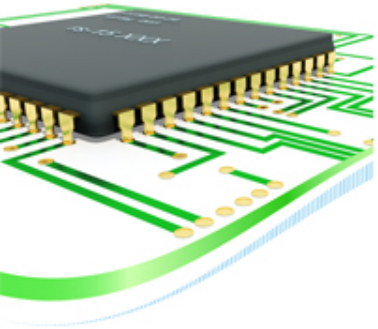
Building up AST



Semantic analysis phase

- **Inherited Attributes (Top-Down)**
- **Synthesized Attributes (Bottom-Up)**

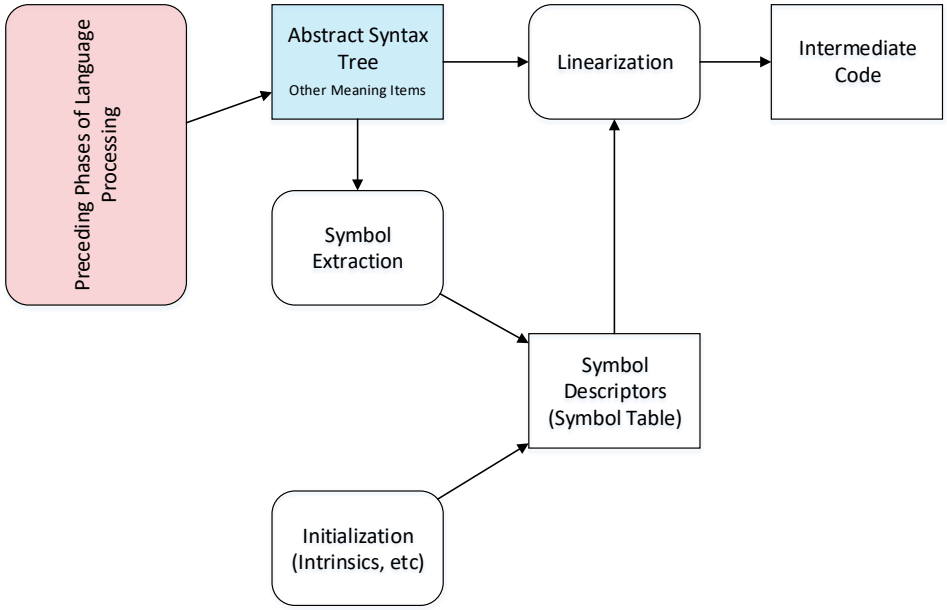
- **Opportune Moments in Parsing!**



IR Generation

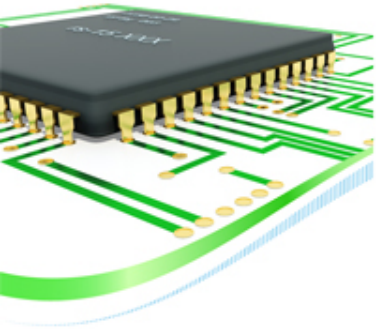
Linear Representations

Building up AST



Build

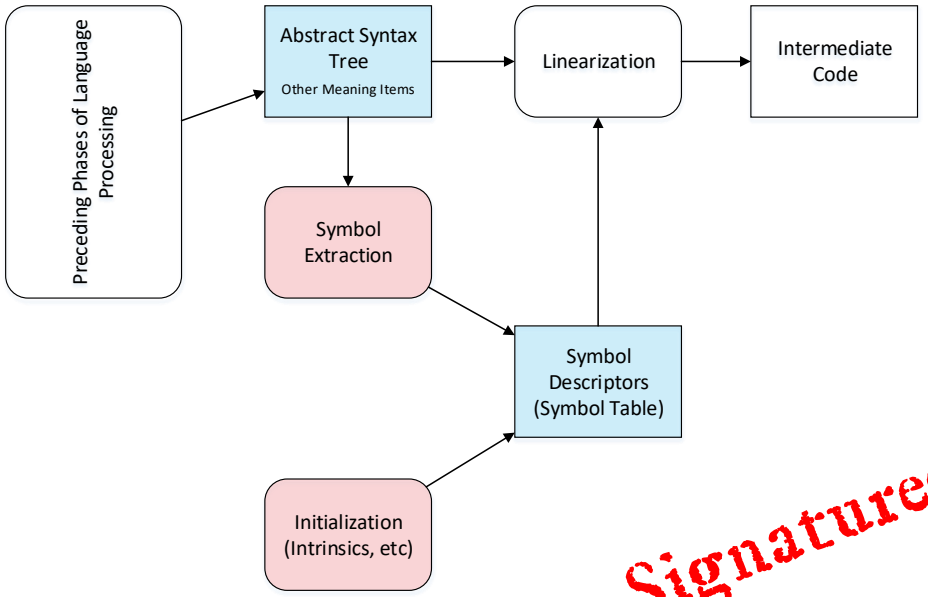
- **Expression Trees**
- **Control Flow Structures**
- **Symbolic Representation Items** (namespaces, classes, types, formal parameters, methods, procedures, variables, …)



IR Generation

Augmentation of AST, DAG

Multi-pass AST



Meta-types & Type Signatures

Initial Setup

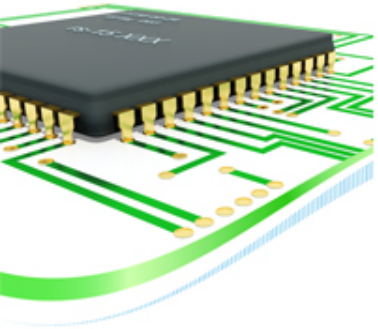
- **Register Intrinsic Symbols**

Symbolic Representation Items

- **Populate the Symbol Entries**
- **Detect Duplications and Conflicts**

Calculation

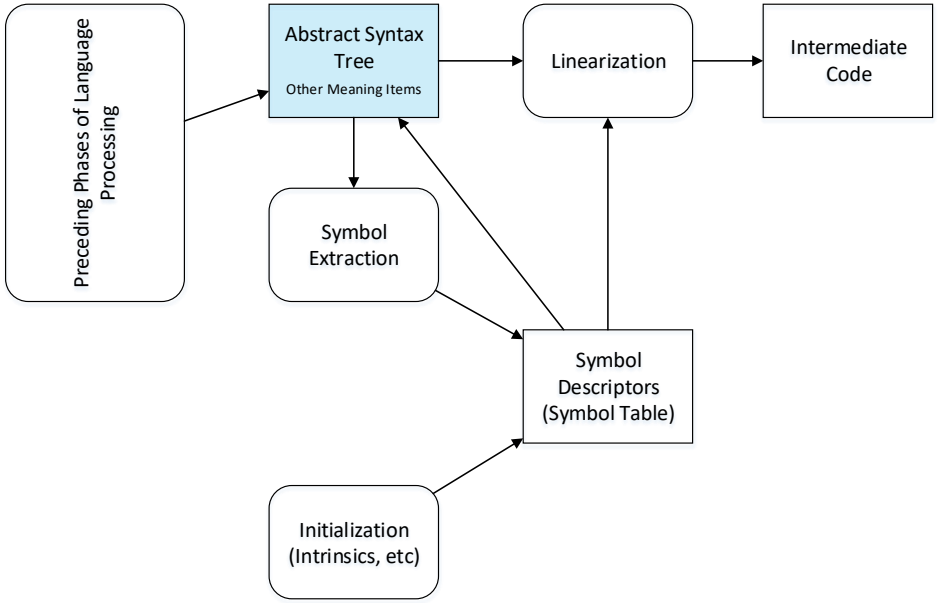
- **Calculate Symbol Address**
- **Type Data**



IR Generation

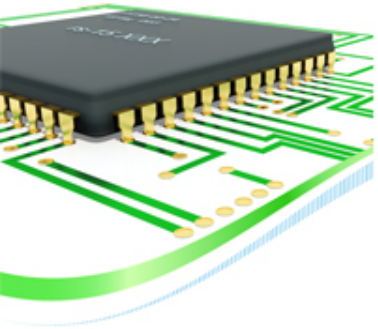
Augmentation and Transformation

Multi-pass AST



Expression Trees

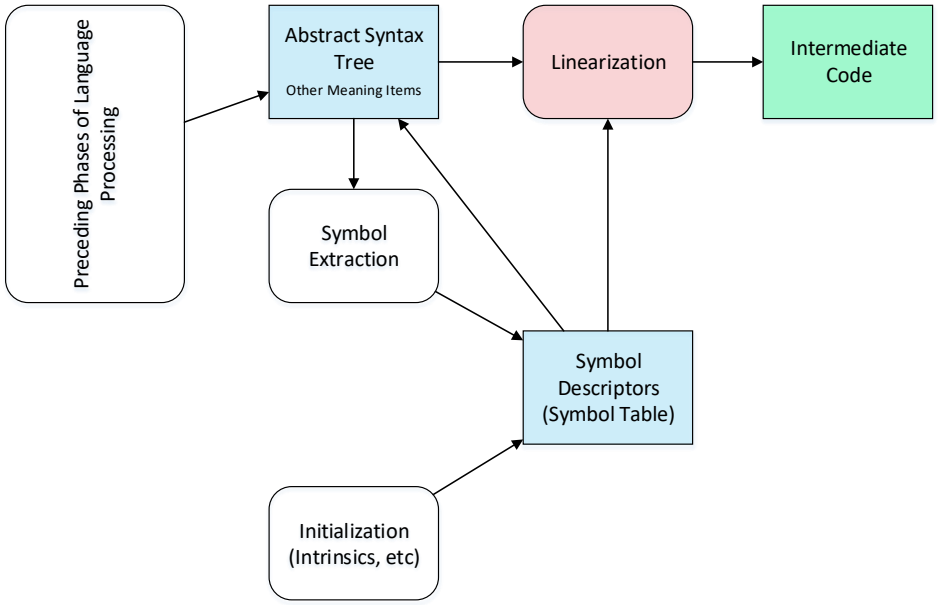
- **Apply Transformation (DAG)**
- **Inject Cast / Pseudo Operators**
- **Evaluate Node Types**
- **Detect errors** (Unresolved symbols, operator applicability, etc.)
- **Apply Constant Folding**
- **Calculate Node Addresses**
- **Calculate Stack Loads**



IR Generation

Linearization

Multi-pass AST

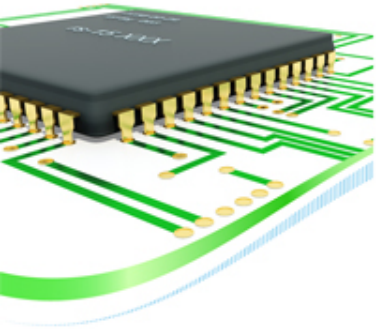


Control Flow Structure

- **Apply Code Templates to Emit IC Instructions**

Expression Trees

- **Traverse and Emit IC Instructions**



IR Generation

Intermediate Code

Purpose

- **Architecture Independence (!)**
- **Standard / Improved Target Code Quality**
- **Reducing Cost of Overall Implementation**

Basic Types

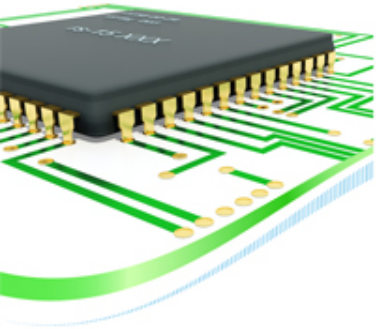
- **Stack Machine Code**
- **Three Address Code**

Examples

- **Gimple / LLVM / JVM**

IC Generation

Example: Gimple



```
float f( int a, int b, float x ) {
    float y = a*x*x + b*x + 100;
    return y;
}
```

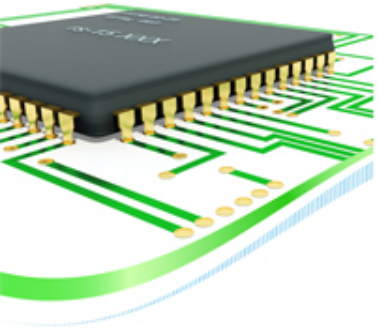
```
f (int a, int b, float x)
{
  float D.1597D.1597;
  float D.1598D.1598;
  float D.1599D.1599;
  float D.1600D.1600;
  float D.1601D.1601;
  float D.1602D.1602;
  float D.1603D.1603;
  float y;

  D.1597D.1597 = (float) a;
  D.1598D.1598 = D.1597D.1597 * x;
  D.1599D.1599 = D.1598D.1598 * x;
  D.1600D.1600 = (float) b;
  D.1601D.1601 = D.1600D.1600 * x;
  D.1602D.1602 = D.1599D.1599 + D.1601D.1601;
  y = D.1602D.1602 + 1.0e+2;
  D.1603D.1603 = y;
  return D.1603D.1603;
}
```

Example from “Douglas Thain, Introduction to Compilers and Language Design, Chapter 8”, http://compilerbook.org

IC Generation

Example: LLVM



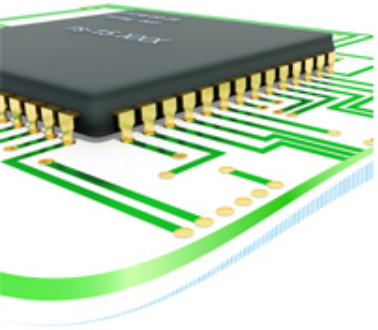
```
float f( int a, int b, float x ) {
    float y = a*x*x + b*x + 100;
    return y;
}
```

```
define float @f(i32 %a, i32 %b, float %x) #0 {
  %1 = alloca i32, align 4
  %2 = alloca i32, align 4
  %3 = alloca float, align 4
  %y = alloca float, align 4
  store i32 %a, i32* %1, align 4
  store i32 %b, i32* %2, align 4
  store float %x, float* %3, align 4
  %4 = load i32* %1, align 4
  %5 = sitofp i32 %4 to float
  %6 = load float* %3, align 4
  %7 = fmul float %5, %6
  %8 = load float* %3, align 4
  %9 = fmul float %7, %8
  %10 = load i32* %2, align 4
  %11 = sitofp i32 %10 to float
  %12 = load float* %3, align 4
  %13 = fmul float %11, %12
  %14 = fadd float %9, %13
  %15 = fadd float %14, 1.000000e+02
  store float %15, float* %y, align 4
  %16 = load float* %y, align 4
  ret float %16
}
```

Example from “Douglas Thain, Introduction to Compilers and Language Design, Chapter 8”, http://compilerbook.org

IC Generation

Example: JVM



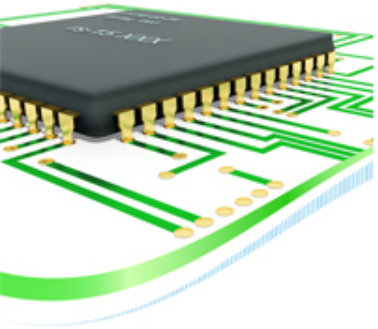
```
float f( int a, int b, float x ) {
    float y = a*x*x + b*x + 100;
    return y;
}
```

```
 0: iload   1
 1: i2f
 2: fload   3
 4: fmul
 5: fload   3
 7: fmul
 8: iload   2
 9: i2f
10: fload   3
12: fmul
13: fadd
14: ldc     #2
16: fadd
17: fstore  4
19: fload   4
21: freturn
```

Example from “Douglas Thain, Introduction to Compilers and Language Design, Chapter 8”, http://compilerbook.org

IC Generation

Example: Proprietary



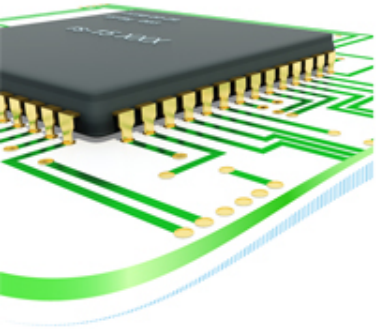
```
float f(int32 a, int32 b, float x)
begin
   float y=a*x*x + b*x + 100;

   return y;
end
```

```
 0 ssr 1[1 0x00000001]                    ; Prologue f S0n(F0ni0ni0nF0n)
 1 ssr 29[52 0x00000034]                  ; Debug expression prologue y=a*x*x + b*x + 100;
 2 psh mwp base pointer offset 0
 3 pmw base pointer offset -5
 4 pmw base pointer offset -3
 5 cvt_F_i -2 regs
 6 mul_F
 7 pmw base pointer offset -3
 8 mul_F
 9 pmw base pointer offset -4
10 pmw base pointer offset -3
11 cvt_F_i -2 regs
12 mul_F
13 add_F
14 psh int8 100 0x64
15 cvt_F_t -1 regs
16 add_F
17 ssr 4[0 0x00000000]                    ; flat
18 ssr 3[1 0x00000001]
19 ssr 29[89 0x00000059]                  ; Debug expression prologue y;
20 pmw base pointer offset 0
21 ssr 5[1 0x00000001]
22 ssr 2[1 0x00000001]                    ; Epilogue f S0n(F0ni0ni0nF0n)
23 rtf 3
24 hlt
```

IC Generation

Multi-pass IR Traversal

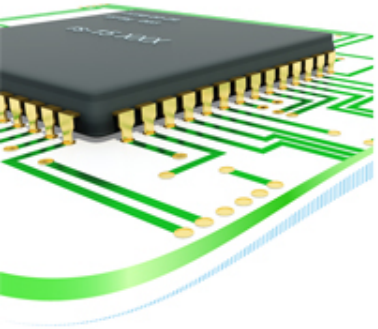


Some Basics

- **Multi-Pass IR Node Traversal**
- **Virtual instructions and types**
- **Control Flow Code Templates**
- **Type Calculation**
- **Address Calculation**
- **Optimizations**
- **More…**

Some Advanced Processing

- **Type System Operations**
- **Structured Exception Handling**
- **Closures**
- **Concurrency Related Patterns**
- **More …**

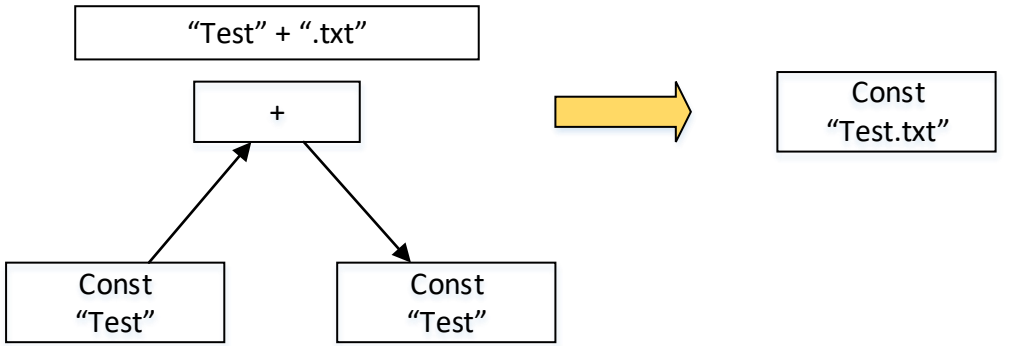


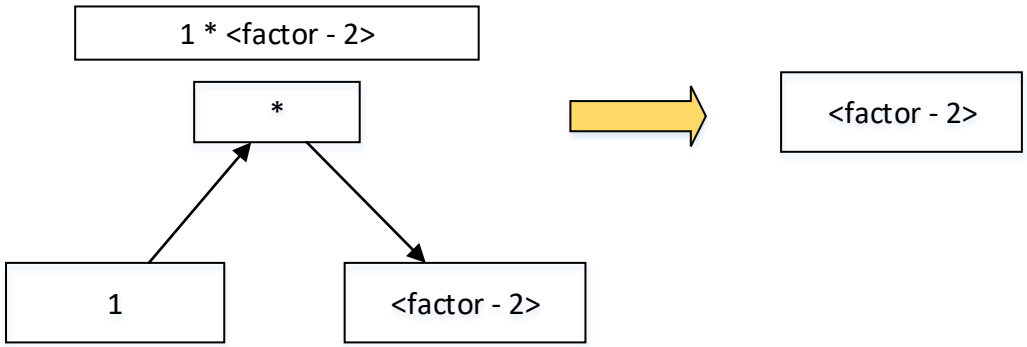
Simple Optimizations on IR

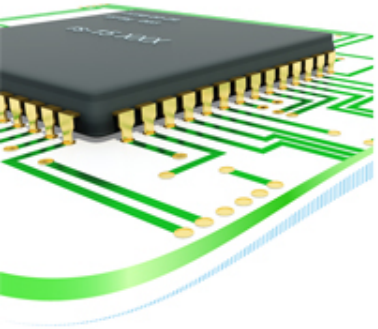
Constant Folding

Arithmetic Logic Operation Properties

- **Constant operands**
- **Identity elements**





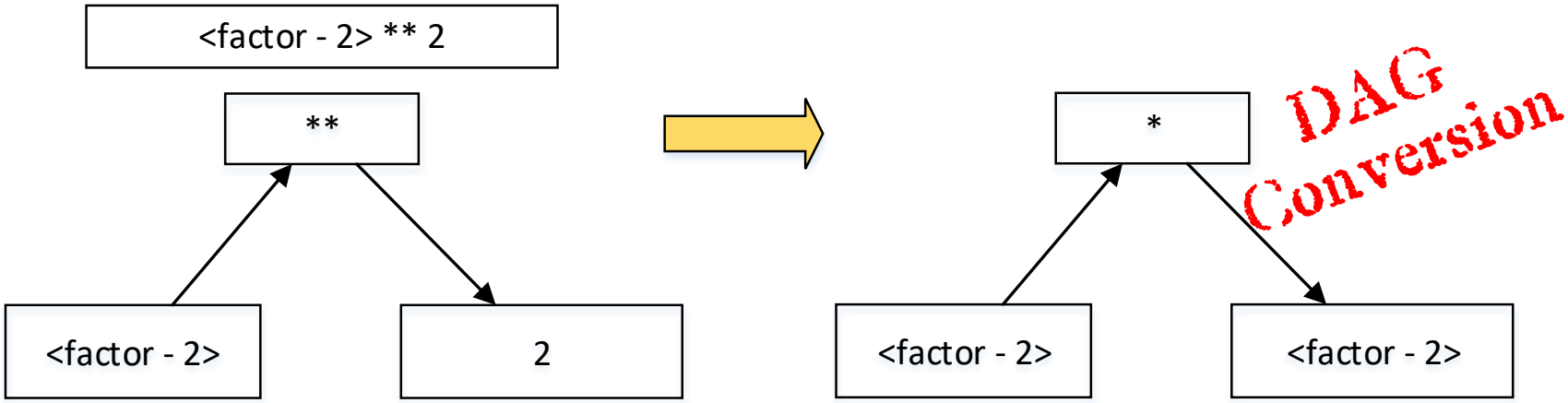


Simple Optimizations on IR

Strength Reduction

Arithmetic Logic Operation Properties

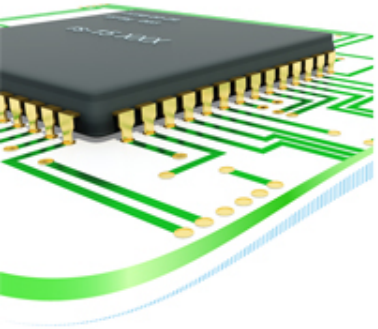
- **Exponentials with constants**
- **Multiplications with constant**
- **More …**



These properties may have impact on instruction selection, too.

Simple Optimizations on IR

Invariant Code Motion – Code Hoisting



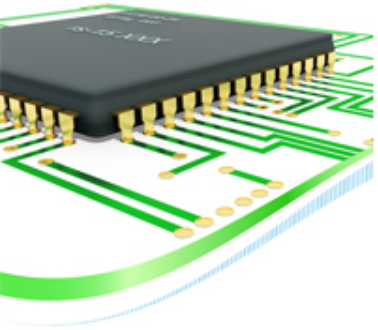
```
let k=0,
    m=0,
    x=random(),
    y=random();

while (m<1000)
{
   delete(num2str(x*y)+".txt");
   m=m+1;
}
```

```
00004 setv      1 type:[]
00005 pop       1 type:[]
00006 call     22 type:[number]
00007 setv      2 type:[]
00008 pop       1 type:[]
00009 call     22 type:[number]
00010 setv      3 type:[]
00011 pop       1 type:[]
00012 id        1 type:[number]
00013 const     0 type:[number] 1000
00014 lt        0 type:[number]
00015 pop       1 type:[]
00016 jf       31 type:[]
00017 id        2 type:[number]
00018 id        3 type:[number]
00019 mul       0 type:[number]
00020 call      1 type:[string]
00021 const     0 type:[string] ".txt"
00022 add       0 type:[string]
00023 call     18 type:[string]
00024 pop       1 type:[]
00025 id        1 type:[number]
00026 const     0 type:[number] 1
00027 add       0 type:[number]
00028 asn       1 type:[number]
00029 pop       1 type:[]
00030 jmp      12 type:[]
```

Move

Example from the TQL assignment

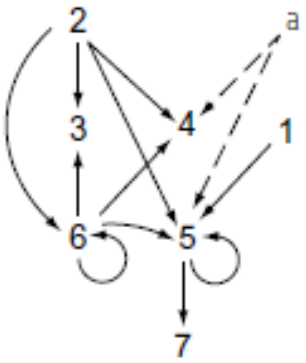


Simple Optimizations on IR

Invariant Code Motion – Code Hoisting

Data Flow Analysis and Dependence Graphs

```
1   x ← 0
2   i ← 1
3   while (i < 100)
4     if (a[i] > 0)
5       then x ← x + a[i]
6     i ← i + 1
7   print x
```

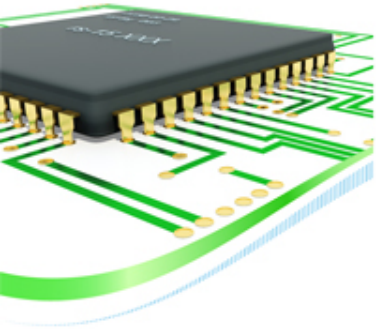


■ **FIGURE 5.4** Interaction between Control Flow and the Dependence Graph.

Excerpt from “Cooper, K.D., Torczon, L.; Engineering A Compiler, 2nd Edition page 233”

Simple Optimizations on IR

Dead Code Elimination



```
let m=0,
    x=0,
    y=random();

x=2*m*y/(m+2);
y=y/3;
x=7/2;
```

```
00000 const     0 type:[number] 0
00001 setv      0 type:[]
00002 pop       1 type:[]
00003 const     0 type:[number] 0
00004 setv      1 type:[]
00005 pop       1 type:[]
00006 call     22 type:[number]
00007 setv      2 type:[]
00008 pop       1 type:[]
00009 const     0 type:[number] 2
00010 id        0 type:[number]
00011 mul       0 type:[number]
00012 id        2 type:[number]
00013 mul       0 type:[number]
00014 id        0 type:[number]
00015 const     0 type:[number] 2
00016 add       0 type:[number]
00017 div       0 type:[number]
00018 asn       1 type:[number]
00019 pop       1 type:[]
00020 id        2 type:[number]
00021 const     0 type:[number] 3
00022 /         0 type:[number]
00023 asn       2 type:[number]
00024 pop       1 type:[]
00025 const     0 type:[number] 3.5
00026 asn       1 type:[number]
00027 pop       1 type:[]
```

Not Effective

Example from the TQL assignment

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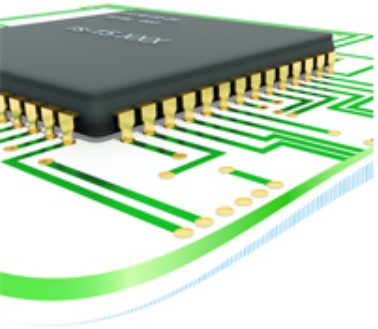
Peephole Optimization



```
let m=0,
    x=0,
    y=random();

x=2*m*y/(m+2);
y=x+1;
```

```
00000 const     0 type:[number] 0
00001 setv      0 type:[]
00002 pop       1 type:[]
00003 const     0 type:[number] 0
00004 setv      1 type:[]
00005 pop       1 type:[]
00006 call     22 type:[number]
00007 setv      2 type:[]
00008 pop       1 type:[]
00009 const     0 type:[number] 2
00010 id        0 type:[number]
00011 mul       0 type:[number]
00012 id        2 type:[number]
00013 mul       0 type:[number]
00014 id        0 type:[number]
00015 const     0 type:[number] 2
00016 add       0 type:[number]
00017 /         0 type:[number]
00018 asn       1 type:[number]
00019 pop       1 type:[]
00020 id        1 type:[number]
00021 const     0 type:[number] 1
00022 add       0 type:[number]
00023 asn       2 type:[number]
00024 pop       1 type:[]
00025 ret       0 type:[]
```

Not Effective

Example from the TQL assignment