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University of Science and Technology of China

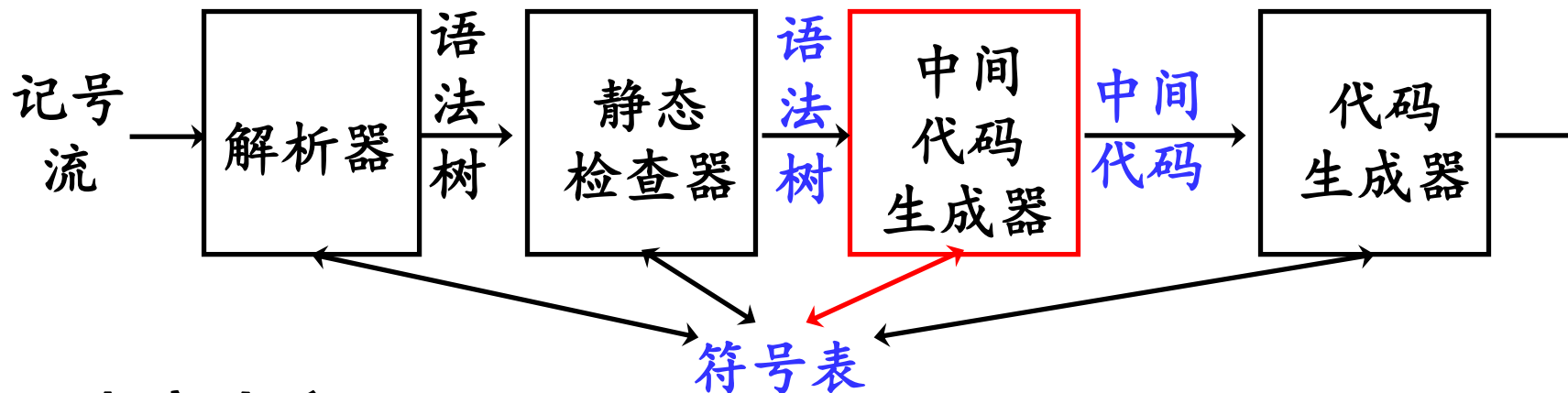
中间语言与中间代码生成 I

《编译原理和技术(H)》、《编译原理(H)》

张昱

0551-63603804, yuzhang@ustc.edu.cn

中国科学技术大学
计算机科学与技术学院



本章内容

- 中间语言：常用的中间表示 (Intermediate Representation)
 - 后缀表示、图表示、三地址代码、[LLVM IR](#)
- 基本块和控制流图
- 中间代码的生成
 - 声明语句 (=>更新符号表)
 - 表达式、赋值语句 (=>产生临时变量、查符号表)
 - 布尔表达式、控制流语句 (=>标号/回填技术、短路计算)



7.1 中间语言

- 后缀形式、图形表示
- 三地址代码
- 静态单赋值



□ 后缀表示(逆波兰式)：运算符在其运算对象之后

$(8 - 5) + 2$ 的后缀表示是 $8 5 - 2 +$ **不需要括号**

前提：
算符无二义

□ 后缀表示的最大优点：便于计算机处理表达式, 如求值、代码生成等

计算栈

输入串

8

8 5 - 2 +

5 - 2 +

8 5

- 2 +

3

2 +

3 2

+

5

每碰到运算对象，就把它压进栈；
每碰到运算符，就从栈顶取出相应个数的运算对象进行计算，再将结果压进栈



□ 后缀表示不需要括号(前提: 算符无二义)

$(8 - 5) + 2$ 的后缀表示是 $8 5 - 2 +$

□ 后缀表示的最大优点是便于计算机处理表达式

□ 后缀表示的表达能能力

- 可以拓广到表示赋值语句和控制语句

适合底层实现的表达

- 但很难用栈来描述控制语句的计算

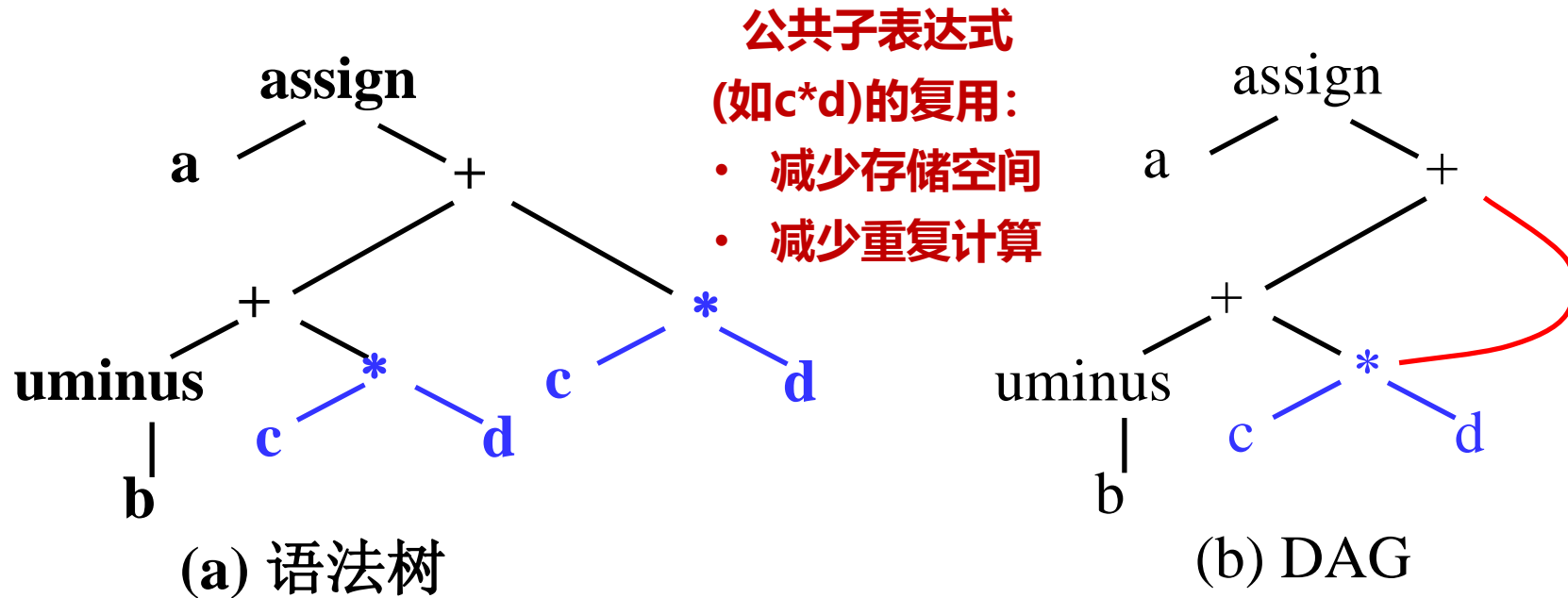
□ 前缀表示 (波兰式)

- 一种逻辑、算术和代数的表示方法, 如 **op**(a, b, c)

- 用于简化命题逻辑的表达

适合上层规范的表达

- 语法树是一种图形化的中间表示
- 有向无环图也是一种中间表示



$a = (-b + c*d) + c*d$ 的图形表示



构造赋值语句语法树的语法制导定义

修改构造结点的函数 *mkNode* 可生成有向无环图:

—判断是否已有**计算等价**的表达式树, 如用 ValueNumbering (VN)

产生式	语义规则
$S \rightarrow id = E$	$S.nptr = mkNode('assign', mkLeaf(id, id.entry), E.nptr)$
$E \rightarrow E_1 + E_2$	$E.nptr = mkNode('+', E_1.nptr, E_2.nptr)$
$E \rightarrow E_1 * E_2$	$E.nptr = mkNode('*', E_1.nptr, E_2.nptr)$
$E \rightarrow -E_1$	$E.nptr = mkUNode('uminus', E_1.nptr)$
$E \rightarrow (E_1)$	$E.nptr = E_1.nptr$
$F \rightarrow id$	$E.nptr = mkLeaf(id, id.entry)$



□ 三地址代码(three-address code)

一般形式: $x = y \text{ op } z$

最多1个算符, 最多3个计算分量(运算对象的地址)

→ 三地址

例 表达式 $x + y * z$ 翻译成的三地址语句序列是

$$t_1 = y * z$$

$$t_2 = x + t_1$$



□ 三地址代码是语法树或DAG的一种线性表示

例 $a = (-b + c * d) + c * d$

语法树的代码

$$t_1 = -b$$

$$t_2 = c * d$$

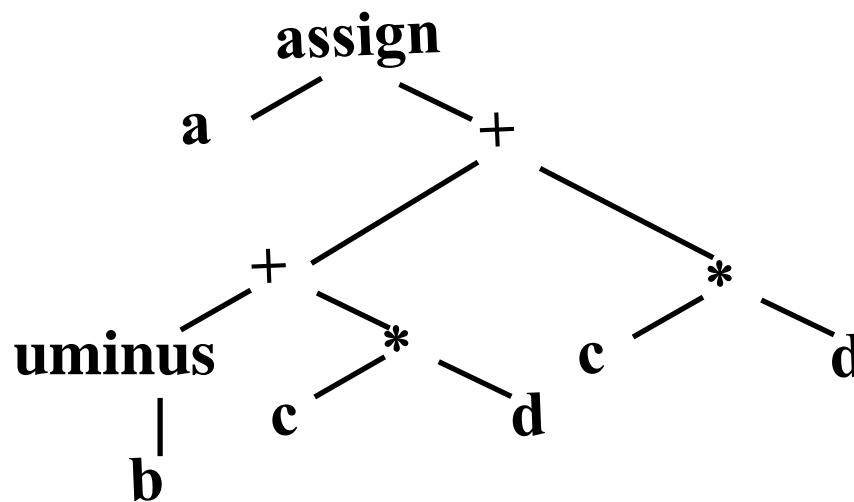
$$t_3 = t_1 + t_2$$

$$t_4 = c * d$$

$$t_5 = t_3 + t_4$$

$$a = t_5$$

存储布局是线性的;
按字节寻址



对语法树进行后序遍历，输出三地址代码

——体现后缀式的应用价值

编译器实现中会建立后序线索化树，方便代码生成、求值等



□ 三地址代码是语法树或DAG的一种线性表示

例 $a = (-b + c * d) + c * d$

语法树的代码

$$t_1 = -b$$

$$t_2 = c * d$$

$$t_3 = t_1 + t_2$$

$$t_4 = c * d$$

$$t_5 = t_3 + t_4$$

$$a = t_5$$

DAG的代码

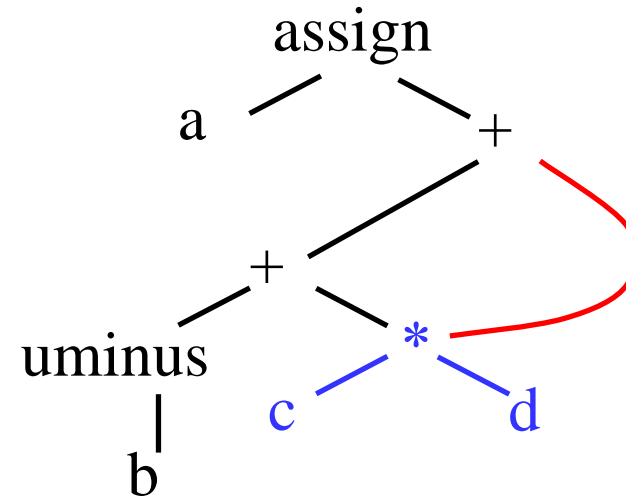
$$t_1 = -b$$

$$t_2 = c * d$$

$$t_3 = t_1 + t_2$$

$$t_4 = t_3 + t_2$$

$$a = t_5$$



(b) DAG

按DAG结点的拓扑序, 输出三地址代码



□ 常用的三地址语句

■ 赋值语句 $x = y \text{ op } z, \quad x = \text{op } y$

■ 复写语句 $x = y$

■ 无条件转移 $\text{goto } L$

■ 条件转移 $\text{if } x \text{ relop } y \text{ goto } L$

■ 过程调用

param x

call p, n

■ 过程返回 $\text{return } y$

■ 索引赋值 $x = y[i]$ 和 $x[i] = y$

■ 地址和指针赋值 $x = \&y, x = *y$ 和 $*x = y$

要注意遵循的约定(convention)

如多个参数的param出现的先后次序

参数设置

调用含n个参数的子过程p



□ 静态单赋值形式(static single-assignment form, SSA)

- 一种便于某些代码优化的中间表示
- 和三地址代码的主要区别

所有赋值指令都是对不同名字的变量的赋值

对p的定值

三地址代码

$$p = a + b$$

$$q = p - c$$

$$p = q * d$$

$$p = e - p$$

$$q = p + q$$

对p的引用

静态单赋值形式

$$p_1 = a + b$$

$$q_1 = p_1 - c$$

$$p_2 = q_1 * d$$

$$p_3 = e - p_2$$

$$q_2 = p_3 + q_1$$

SSA的优势: 明确知道
所引用的变量在哪定值



- 一种便于某些代码优化的中间表示
- 和三地址代码的主要区别

所有赋值指令都是对不同名字的变量的赋值

同一个变量在不同控制流路径上都被定值的解决办法:

```
if (flag) x = -1; else x = 1;
```

```
y = x * a;
```

改成

```
if (flag)  $x_1 = -1$ ; else  $x_2 = 1$ ;
```

```
 $x_3 = \phi(x_1, x_2)$ ; // 由flag的值决定用 $x_1$ 还是 $x_2$ 
```

```
y =  $x_3$  * a;
```

Phi算子: 汇合对
多个可能定值的引用



7.2 基本块和控制流图

- 基本块
- 流图



□ 程序举例

源程序

```

prod = 0;
i = 1;
do {
  prod = prod + a[i] * b[i];
  i = i + 1;
} while (i <= 20);

```

第*i*个元素的
类型为int

三地址码

(1) prod = 0

(2) i = 1

(3) $t_1 = 4 * i$

(4) $t_2 = a[t_1]$

(5) $t_3 = 4 * i$

(6) $t_4 = b[t_3]$

(7) $t_5 = t_2 * t_4$

(8) $t_6 = prod + t_5$

(9) prod = t_6

(10) $t_7 = i + 1$

(11) i = t_7

(12) if i <= 20 goto (3)

元素的地址要转
换成按字节寻址



□ 基本块(basic block)

- 是连续的语句序列
- 控制流从它的开始进入-单入口, 并从它的末尾离开-单出口, 没有停止或分支的可能性(末尾除外)

□ 流图(flow graph)

- 用有向边表示基本块之间的控制流信息
- 基本块作为流图的结点

(1) $\text{prod} = 0$

(2) $i = 1$

(3) $t_1 = 4 * i$

(4) $t_2 = a[t_1]$

(5) $t_3 = 4 * i$

(6) $t_4 = b[t_3]$

(7) $t_5 = t_2 * t_4$

(8) $t_6 = \text{prod} + t_5$

(9) $\text{prod} = t_6$

(10) $t_7 = i + 1$

(11) $i = t_7$

(12) **if $i \leq 20$ goto (3)**



□ 基本块的划分方法

- 首先确定所有入口语句
 - 序列的第一个语句
 - 能由(无)条件转移语句转到的语句
 - 紧跟在(无)条件转移语句后面的语句
- 每个入口语句到下一个入口语句之前（或到程序结束）的语句序列构成一个基本块

(1) $\text{prod} = 0$

(2) $i = 1$

(3) $t_1 = 4 * i$

(4) $t_2 = a[t_1]$

(5) $t_3 = 4 * i$

(6) $t_4 = b[t_3]$

(7) $t_5 = t_2 * t_4$

(8) $t_6 = \text{prod} + t_5$

(9) $\text{prod} = t_6$

(10) $t_7 = i + 1$

(11) $i = t_7$

(12) **if $i \leq 20$ goto (3)**



- (1) $\text{prod} = 0$
- (2) $i = 1$
- (3) $t_1 = 4 * i$
- (4) $t_2 = a[t_1]$
- (5) $t_3 = 4 * i$
- (6) $t_4 = b[t_3]$
- (7) $t_5 = t_2 * t_4$
- (8) $t_6 = \text{prod} + t_5$
- (9) $\text{prod} = t_6$
- (10) $t_7 = i + 1$
- (11) $i = t_7$
- (12) if $i \leq 20$ goto (3)

(1) $\text{prod} = 0$
(2) $i = 1$

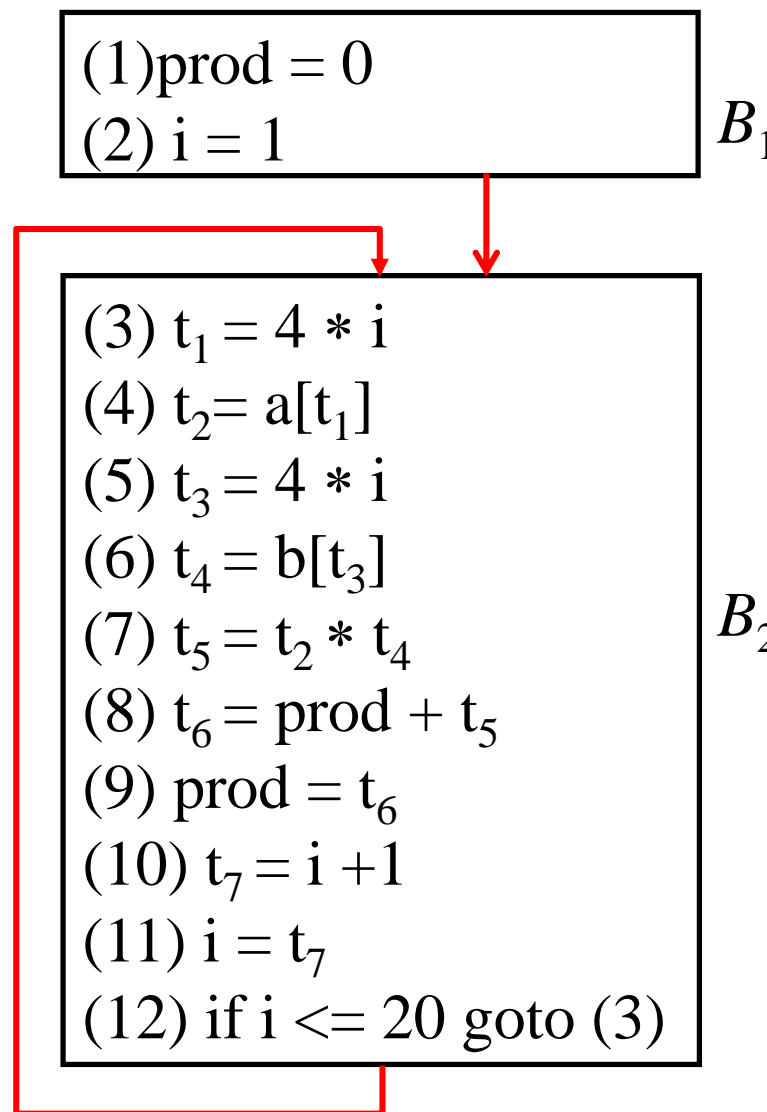
B_1

(3) $t_1 = 4 * i$
(4) $t_2 = a[t_1]$
(5) $t_3 = 4 * i$
(6) $t_4 = b[t_3]$
(7) $t_5 = t_2 * t_4$
(8) $t_6 = \text{prod} + t_5$
(9) $\text{prod} = t_6$
(10) $t_7 = i + 1$
(11) $i = t_7$
(12) if $i \leq 20$ goto (3)

B_2



- (1) **prod = 0**
- (2) **i = 1**
- (3) **t₁ = 4 * i**
- (4) **t₂ = a[t₁]**
- (5) **t₃ = 4 * i**
- (6) **t₄ = b[t₃]**
- (7) **t₅ = t₂ * t₄**
- (8) **t₆ = prod + t₅**
- (9) **prod = t₆**
- (10) **t₇ = i + 1**
- (11) **i = t₇**
- (12) **if i <= 20 goto (3)**





流图(变换成 SSA 格式)

```
(1) prod = 0
(2) i = 1
```

B_1

```
(3) t1 = 4 * i
(4) t2 = a[t1]
(5) t3 = 4 * i
(6) t4 = b[t3]
(7) t5 = t2 * t4
(8) t6 = prod + t5
(9) prod = t6
(10) t7 = i + 1
(11) i = t7
(12) if i <= 20 goto (3)
```

B_2

```
(1) prod1 = 0
(2) i1 = 1
(3) i3 = φ(i1, i2)
(4) prod3 = φ(prod1, prod2)
(5) t1 = 4 * i3
(6) t2 = a[t1]
(7) t3 = 4 * i3
(8) t4 = b[t3]
(9) t5 = t2 * t4
(10) t6 = prod3 + t5
(11) prod2 = t6
(12) t7 = i3 + 1
(13) i2 = t7
(14) if i2 <= 20 goto (3)
```

插入到块 B_2 入口处

```
(1) prod1 = 0
(2) i1 = 1
```

B_1

```
(3) i3 = φ(i1, i2)
(4) prod3 = φ(prod1, prod2)
(5) t1 = 4 * i3
(6) t2 = a[t1]
(7) t3 = 4 * i3
(8) t4 = b[t3]
(9) t5 = t2 * t4
(10) t6 = prod3 + t5
(11) prod2 = t6
(12) t7 = i3 + 1
(13) i2 = t7
(14) if i2 <= 20 goto (3)
```

B_2

利用流图, 可快速找到 B_2 的前驱基本块, 按控制流逆向找到最近对 i 和 $prod$ 的定值

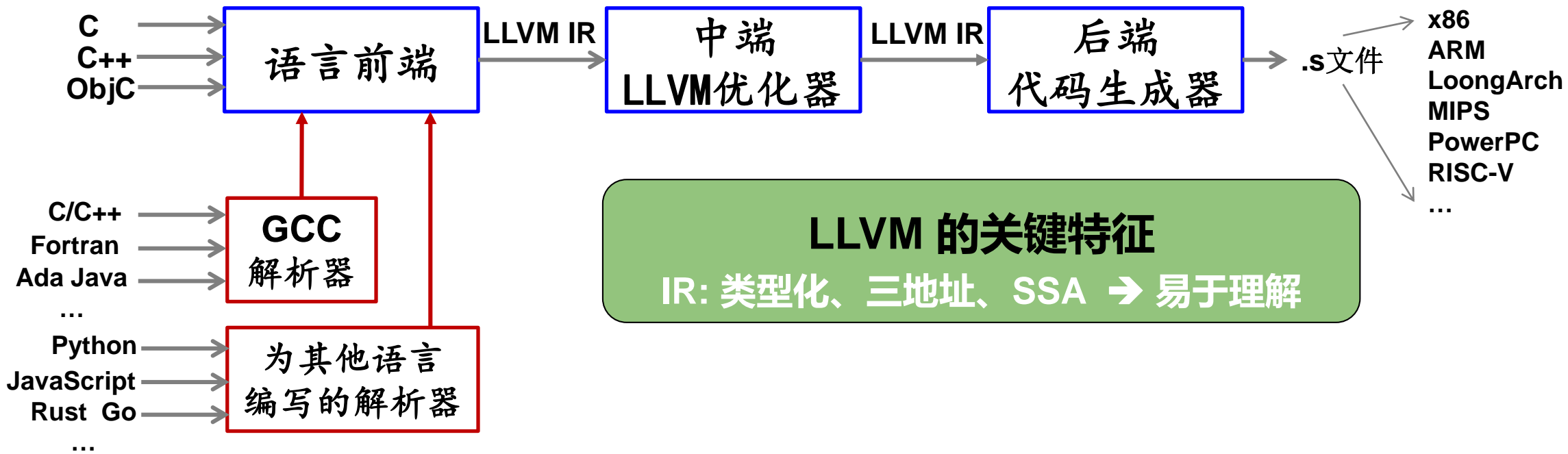


7.3 LLVM 编译系统与LLVM IR

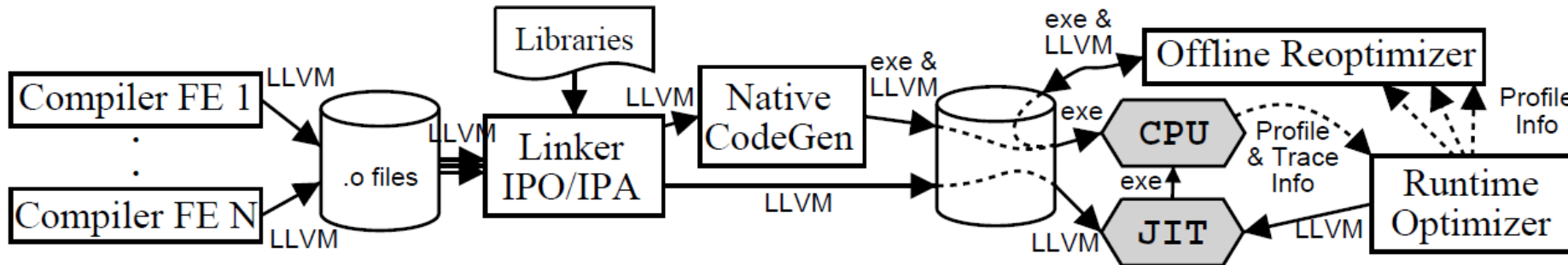
- 总体结构
- LLVM IR
- LLVM Pass Manager
- LLVM Tools



LLVM编译系统



LLVM 的关键特征
 IR: 类型化、三地址、SSA → 易于理解





□ 基础工具

- **llvm-as: Convert from .ll (text) to .bc (binary)**
- **llvm-dis: Convert from .bc (binary) to .ll (text)**
- **llvm-link: Link multiple .bc files together**
- **llvm-prof: Print profile output to human readers**
- **llvmc: Configurable compiler driver**

□ 集成工具

- **bugpoint: automatic compiler debugger**
- **llvm-gcc/llvm-g++: C/C++ compilers**



□ 参考资料

- LLVM IR参考手册 (<http://llvm.org/docs/LangRef.html>)
- 教程(<http://llvm.org/docs/tutorial/LangImpl03.html>)

□ 主要特征

- RISC风格的三地址代码
- SSA格式、无限的虚拟寄存器
- 简单、低级的控制流结构
- load/store指令带类型化指针

□ IR的格式: text(.ll)、binary(.bc)、in-memory

```
g++ f.cpp `llvm-config --cxxflags --ldflags --libs --system-libs` -o f
```




□ 编译C文件

- 若是C++文件，则将gcc或clang换成g++或clang++

```
gcc -S f.c -o f-gcc.s           # 编译生成汇编文件
clang -S f.c -o f-clang.s       # 编译生成汇编文件

clang -emit-llvm -S f.c -o f.ll  # 编译生成.ll文件
clang -emit-llvm -c f.c -o f.bc  # 编译生成.bc文件

lli f.ll                        # 执行f.ll
lli f.bc                         # 执行f.bc

llvm-dis < f.bc | less          # 反汇编
llc f.bc -o f.s                 # 编译生成汇编文件
```

<https://llvm.org/docs/GettingStarted.html#an-example-using-the-llvm-tool-chain>



C program language

LLVM IR

-
- | | |
|--|-------------------------|
| <ul style="list-style-type: none">• Scope: <i>file, function</i> | <i>module, function</i> |
|--|-------------------------|
-
- | | |
|---|-------------------------------|
| <ul style="list-style-type: none">• Type: <i>bool, char, int, struct{int, char}</i> | <i>i1, i8, i32, {i32, i8}</i> |
|---|-------------------------------|
-
- | | |
|---|---|
| <ul style="list-style-type: none">• A statement with multiple expressions | A sequence of instructions each of which is in a form of “ <i>x = y op z</i> ”. |
|---|---|
-
- | | |
|--|--|
| <ul style="list-style-type: none">• Data-flow:
a sequence of reads/writes on variables | <ol style="list-style-type: none">1. load the values of memory addresses (variables) to registers;2. compute the values in registers;3. store the values of registers to memory addresses <p>* each register must be assigned exactly once (SSA)</p> |
|--|--|
-
- | | |
|---|--|
| <ul style="list-style-type: none">• Control-flow in a function:
if, for, while, do while, switch-case,... | A set of basic blocks each of which ends with a conditional jump (or return) |
|---|--|



□ 类型系统的组成

- **Primitives:** integer, floating point, label, void

- no “signed” integer types

- arbitrary bitwidth integers (i32, i64, i1)

- **Derived:** pointer, array, structure, function, vector,...

No high-level types: type-system is language neutral!

□ Type system allows arbitrary casts:

- Allows expressing weakly-typed languages, like C

- *Front-ends can implement safe languages*

- *Also easy to define a type-safe subset of LLVM*



示例：C 编译到LLVM

```
int callee(const int *X) {  
    return *X+1; // load  
}  
int caller() {  
    int T; // on stack  
    T = 4; // store  
    return callee(&T);  
}
```

Stack allocation is
explicit in LLVM

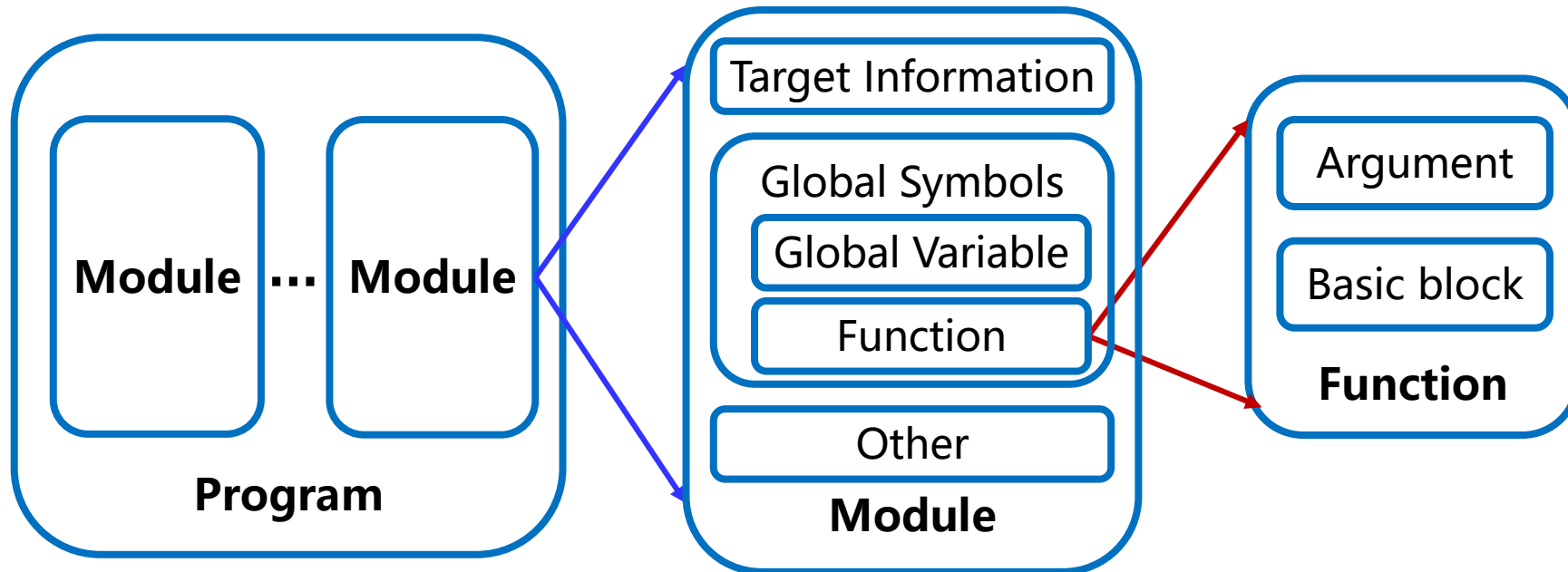
All loads/stores are
explicit in the LLVM
representation

```
define internal i32 @callee(i32* %X) {  
entry:  
    %tmp2 = load i32* %X  
    %tmp3 = add i32 %tmp2, 1  
    ret i32 %tmp3  
}  
  
define internal i32 @caller() {  
entry:  
    %T = alloca i32  
    store i32 4, i32* %T  
    %tmp1 = call i32 @callee( i32* %T )  
    ret i32 %tmp1  
}
```



LLVM IR的程序结构

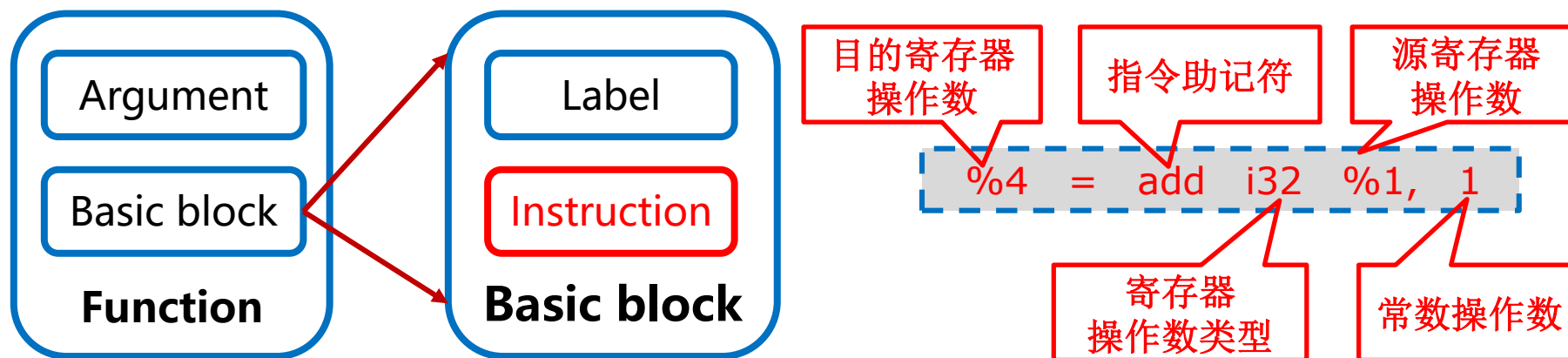
- 模块Module: 包含函数和全局变量
 - 是编译/分析/优化的基本单位, 对应一个程序文件
- 函数Function: 包含基本块/参数
- 基本块BasicBlock: 指令序列





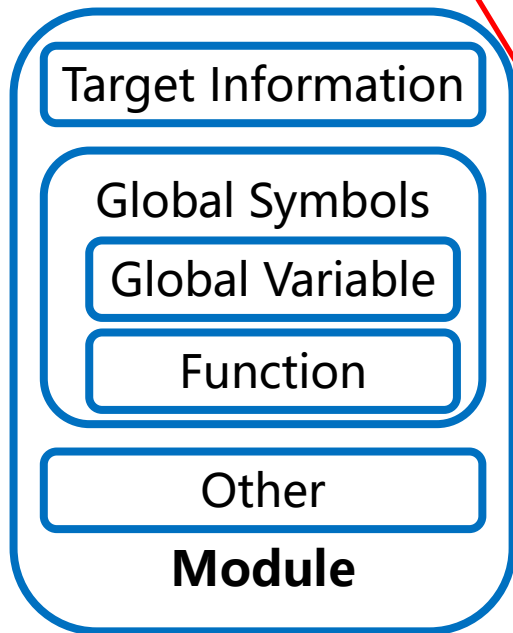
LLVM IR的程序结构

- **模块Module: 包含函数和全局变量**
 - 是编译/分析/优化的基本单位, 对应一个程序文件
- **函数Function: 包含基本块/参数**
- **基本块BasicBlock: 指令序列**
- **指令Instruction: opcode + vector of operands**
 - 所有操作数operands都有类型、指令结果是类型化的





Module结构



全局标识符

```
#include <stdio.h>
int main(){
    printf("hello, world\n");
    return 0;
}
helloworld.c
```

\$1: 程序文件名
\$2: 附加的参数,
如 -m32 表示生成
32位机器代码

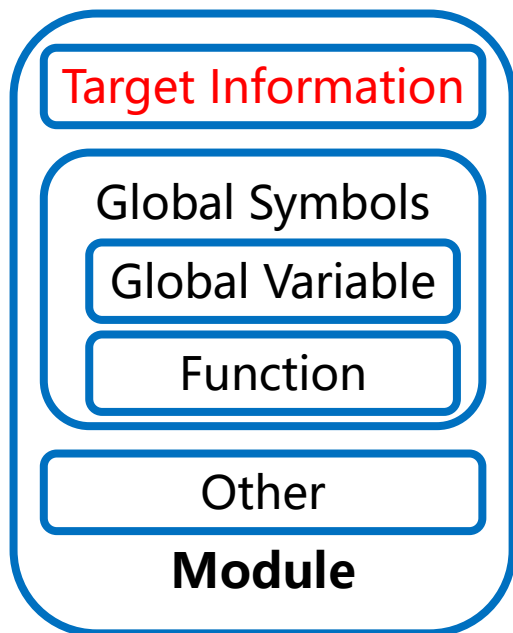
```
clang -emit-llvm -S $1.c -o $1$2.ll $2
```

```
target datalayout = "e-m:e-p270:32:32-p271:32:32-p272:64:64-i64:64-f80:128-
n8:16:32:64-S128"
target triple = "x86_64-pc-linux-gnu"
@.str = private unnamed_addr constant [15 x i8] c"hello,\C2\A0world\0A\00", align 1
; Function Attrs: noinline nounwind optnone uwtable
define dso_local i32 @main() #0 {
    %1 = alloca i32, align 4
    store i32 0, i32* %1, align 4
    %2 = call i32 @printf(i8* getelementptr inbounds ([15 x i8], [15 x i8]*
@.str, i64 0, i64 0))
    ret i32 0
}
declare dso_local i32 @printf(i8*, ...) #1
```

局部标识符



□ Module结构



```
#include <stdio.h>
int main(){
    printf("hello, world\n");
    return 0;
}
helloworld.c
```

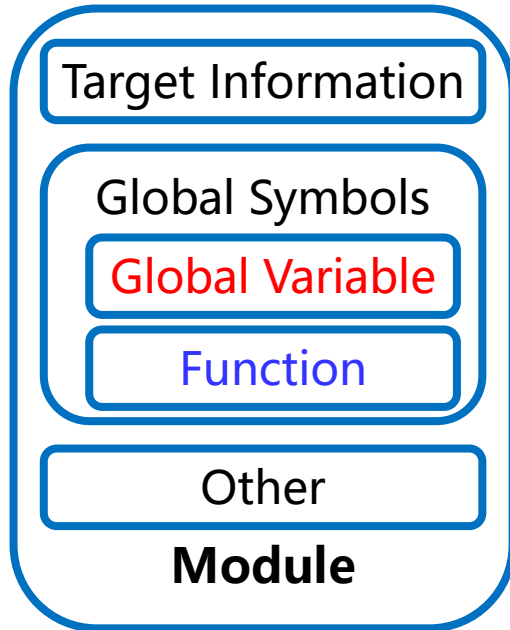
目标内存排布信息

```
target datalayout = "e-m:e-p270:32:32-p271:32:32-p272:64:64-i64:64-f80:128-
n8:16:32:64-S128"
target triple = "x86_64-pc-linux-gnu"
@.str = private unnamed_addr constant [15 x i8] c"hello,\C2\A0world\0A\00", align 1
; Function Attrs: noinline nounwind optnone uwtable
define dso_local i32 @main() #0 {
    %1 = alloca i32, align 4
    store i32 0, i32* %1, align 4
    %2 = call i32 @printf(i8*, ...) @printf(i8* getelementptr inbounds ([15 x i8], [15 x i8]*
@.str, i64 0, i64 0))
    ret i32 0
}
declare dso_local i32 @printf(i8*, ...) #1
```

目标宿主信息



□ Module结构



```
#include <stdio.h>
int main(){
    printf("hello, world\n");
    return 0;
}
helloworld.c
```

```
target datalayout = "e-m:e-p270:32:32-p271:32:32-p272:64:64-i64:64-f80:128-
n8:16:32:64-S128"
target triple = "x86_64-pc-linux-gnu"
@.str = private unnamed_addr constant [15 x i8] c"hello,\C2\A0world\0A\00", align 1
; Function Attrs: noinline nounwind optnone uwtable
define dso_local i32 @main() #0 {
    %1 = alloca i32, align 4
    store i32 0, i32* %1, align 4
    %2 = call i32 @printf(i8*, ...) @printf(i8* getelementptr inbounds ([15 x i8], [15 x i8]* @.str,
i64 0, i64 0))
    ret i32 0
}
declare dso_local i32 @printf(i8*, ...) #1
```

全局变量定义

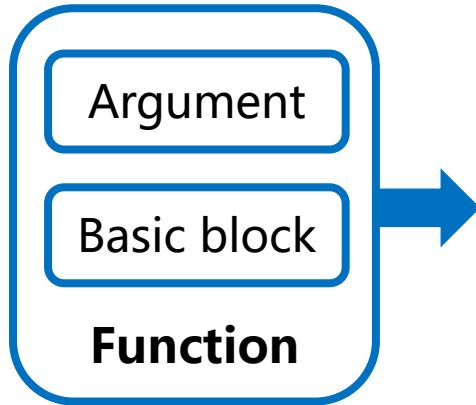
函数定义

函数声明



□ Function结构

dso: dynamic shared object
dso_local: 链接范围限制在所属模块内
dso_preemptable:
 在运行时可能被外部符号取代



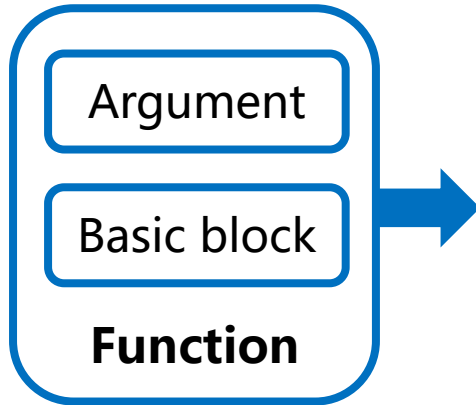
```
double foo();
double bar(float a) {
    return foo(a, 4.0) + bar(31337);
}
```

```
, Function Attrs: noline nounwind optnone uwtable
define dso_local double @bar(float %0) #0 {
    %2 = alloca float, align 4
    store float %0, float* %2, align 4
    %3 = load float, float* %2, align 4
    %4 = fpext float %3 to double
    %5 = call double (double, double, ...) bitcast (double (...)* @foo to
double (double, double, ...)*(double %4, double 4.000000e+00)
    %6 = call double @bar(float 3.133700e+04)
    %7 = fadd double %5, %6
    ret double %7
}

declare double @foo(...) #1
```



□ Function结构



```
double foo();
double bar(float a) {
    return foo(a, 4.0) + bar(31337);
}
```

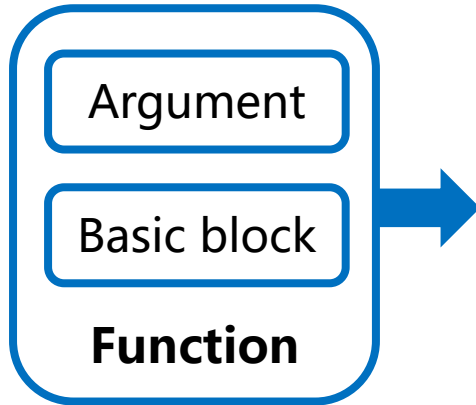
```
; Function Attrs: noline nounwind optnone uwtable
define dso_local double @bar(float %0) #0 {
    %2 = alloca float, align 4
    store float %0, float* %2, align 4
    %3 = load float, float* %2, align 4
    %4 = fpext float %3 to double
    %5 = call double (double, double, ...) bitcast (double (...)* @foo to
double (double, double, ...)*(double %4, double 4.000000e+00)
    %6 = call double @bar(float 3.133700e+04)
    %7 = fadd double %5, %6
    ret double %7
}

declare dso_local double @foo(...) #1
```

参数%0的值存储到新分配的虚拟寄存器%2
不仅指明了类型，还指明了按多少字节齐



□ Function结构



```
double foo();
double bar(float a) {
    return foo(a, 4.0) + bar(31337);
}
```

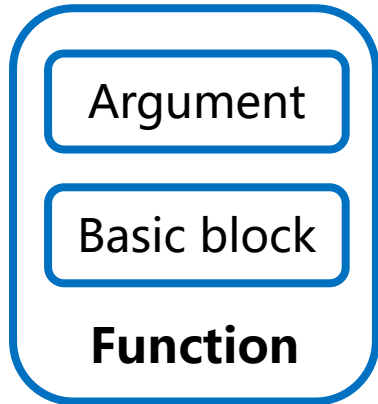
```
; Function Attrs: noline nounwind optnone uwtable
define dso_local double @bar(float %0) #0 {
    %2 = alloca float, align 4
    store float %0, float* %2, align 4
    %3 = load float, float* %2, align 4
    %4 = fpext float %3 to double
    %5 = call double (double, double, ...) bitcast (double (...)* @foo to
double (double, double, ...)*(double %4, double 4.000000e+00)
    %6 = call double @bar(float 3.133700e+04)
    %7 = fadd double %5, %6
    ret double %7
}

declare dso_local double @foo(...) #1
```

加载参数值，将float类型的数扩展为double型
自动类型提升：
float→double



□ Function结构



```
double foo();
double bar(float a) {
    return foo(a, 4.0) + bar(31337);
}
```

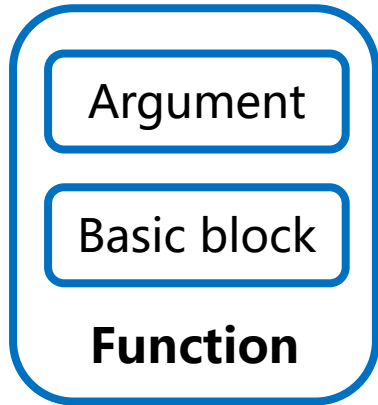
```
; Function Attrs: noline nounwind optnone uwtable
define dso_local double @bar(float %0) #0 {
    %2 = alloca float, align 4
    store float %0, float* %2, align 4
    %3 = load float, float* %2, align 4
    %4 = fpext float %3 to double
    %5 = call double (double, double, ...) bitcast
(double (...)* @foo to double (double,
double, ...)*)(double %4, double 4.000000e+00)
    %6 = call double @bar(float 3.133700e+04)
    %7 = fadd double %5, %6
    ret double %7
}

declare dso_local double @foo(...) #1
```

调用foo函数，将foo强制为至少有2个double型参数的函数类型
bitcast强制类型转换



□ Function结构



```
double foo();
double bar(float a) {
    return foo(a, 4.0) + bar(31337);
}
```

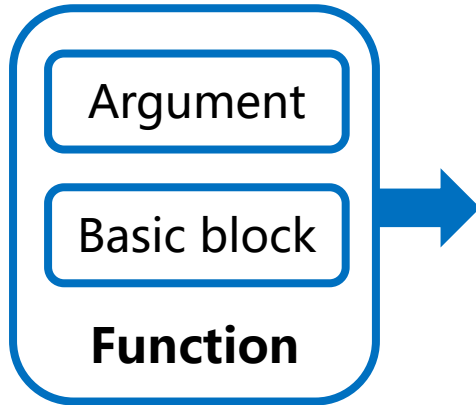
```
; Function Attrs: noline nounwind optnone uwtable
define dso_local double @bar(float %0) #0 {
    %2 = alloca float, align 4
    store float %0, float* %2, align 4
    %3 = load float, float* %2, align 4
    %4 = fpext float %3 to double
    %5 = call double @foo(double, double, ...) bitcast
(double (...)* @foo to double (double,
double, ...)*)(double %4, double 4.000000e+00)
    %6 = call double @bar(float 3.133700e+04)
    %7 = fadd double %5, %6
    ret double %7
}

declare dso_local double @foo(...) #1
```

调用bar
31337看成float



□ Function结构



```
double foo();  
double bar(float a) {  
    return foo(a, 4.0) + bar(31337);  
}
```

```
; Function Attrs: noline nounwind optnone uwtable  
define dso_local double @bar(float %0) #0 {  
    %2 = alloca float, align 4  
    store float %0, float* %2, align 4  
    %3 = load float, float* %2, align 4  
    %4 = fpext float %3 to double  
    %5 = call double @foo(float, double, ...) bitcast  
    (double (...)* @foo to double (double,  
double, ...)*)(double %4, double 4.000000e+00)  
    %6 = call double @bar(float 3.133700e+04)  
    %7 = fadd double %5, %6  
    ret double %7  
}  
  
declare dso_local double @foo(...) #1
```

执行double类型的fadd
运算，将计算结果返回



□ 基本块和流图

```

define dso_local void @f(i32* %0) #0 {
  %2 = alloca i32*, align 8
  %3 = alloca i32, align 4
  %4 = alloca i32, align 4
  store i32* %0, i32** %2, align 8
  store i32 0, i32* %3, align 4
  br label %5

5:                                ; preds = %14, %1
  %6 = load i32, i32* %3, align 4
  %7 = icmp slt i32 %6, 10
  br i1 %7, label %8, label %17

8:                                ; preds = %5
  %9 = load i32*, i32** %2, align 8
  %10 = load i32, i32* %3, align 4
  %11 = sext i32 %10 to i64
  %12 = getelementptr inbounds i32, i32* %9, i64 %11
  %13 = call i32 @Sum(i32*, i32*, ...) bitcast (i32 (...)* @Sum
to i32 (i32*, i32*, ...)*(i32* %12, i32* %4)
  br label %14

```

```

#define N 10
void f(int A[])
{
    int i, P;
    for (i = 0; i < N; ++i)
        Sum(&A[i], &P);
}

```

分配局部变量, %3和 %4分别对应 i 和 P



□ 基本块和流图

```
define dso_local void @f(i32* %0) #0 {
  %2 = alloca i32*, align 8
  %3 = alloca i32, align 4
  %4 = alloca i32, align 4
  store i32* %0, i32** %2, align 8
  store i32 0, i32* %3, align 4
  br label %5

5:                                ; preds = %14, %1
  %6 = load i32, i32* %3, align 4
  %7 = icmp slt i32 %6, 10
  br i1 %7, label %8, label %17

8:                                ; preds = %5
  %9 = load i32*, i32** %2, align 8
  %10 = load i32, i32* %3, align 4
  %11 = sext i32 %10 to i64
  %12 = getelementptr inbounds i32, i32* %9, i64 %11
  %13 = call i32 @Sum to i32 (i32*, i32*, ...)* bitcast (i32 (...)*
  @Sum to i32 (i32*, i32*, ...)*)(i32* %12, i32* %4)
  br label %14
```

```
#define N 10
void f(int A[])
{
    int i, P;
    for (i = 0; i < N; ++i)
        Sum(&A[i], &P);
}
```

无条件跳转到标号为5
的语句
br label 标号



□ 基本块和流图

```

.....
5:                                ; preds = %14, %1
  %6 = load i32, i32* %3, align 4
  %7 = icmp slt i32 %6, 10
  br i1 %7, label %8, label %17

8:                                ; preds = %5
  %9 = load i32*, i32** %2, align 8
  %10 = load i32, i32* %3, align 4
  %11 = sext i32 %10 to i64
  %12 = getelementptr inbounds i32, i32* %9, i64 %11
  %13 = call i32 @Sum(i32*, i32*, ...), i32* %12, i32* %4
  br label %14

14:                               ; preds = %8
  %15 = load i32, i32* %3, align 4
  %16 = add nsw i32 %15, 1
  store i32 %16, i32* %3, align 4
  br label %5

```

```

#define N 10
void f(int A[])
{
    int i, P;
    for (i = 0; i < N; ++i)
        Sum(&A[i], &P);
}

```

基本块5的前驱基本块
分别是标号为14和1两个基本块
preds 指明前驱的标号



□ 基本块和流图

```

.....
5:                ; preds = %14, %1
  %6 = load i32, i32* %3, align 4
  %7 = icmp slt i32 %6, 10
  br i1 %7, label %8, label %17

8:                ; preds = %5
  %9 = load i32*, i32** %2, align 8
  %10 = load i32, i32* %3, align 4
  %11 = sext i32 %10 to i64
  %12 = getelementptr inbounds i32, i32* %9, i64 %11
  %13 = call i32 @Sum to i32 (i32*, i32*, ...)* (i32* %12, i32* %4)
  br label %14

14:               ; preds = %8
  %15 = load i32, i32* %3, align 4
  %16 = add nsw i32 %15, 1
  store i32 %16, i32* %3, align 4
  br label %5, !llvm.loop !6

```

```

#define N 10
void f(int A[])
{
    int i, P;
    for (i = 0; i < N; ++i)
        Sum(&A[i], &P);
}

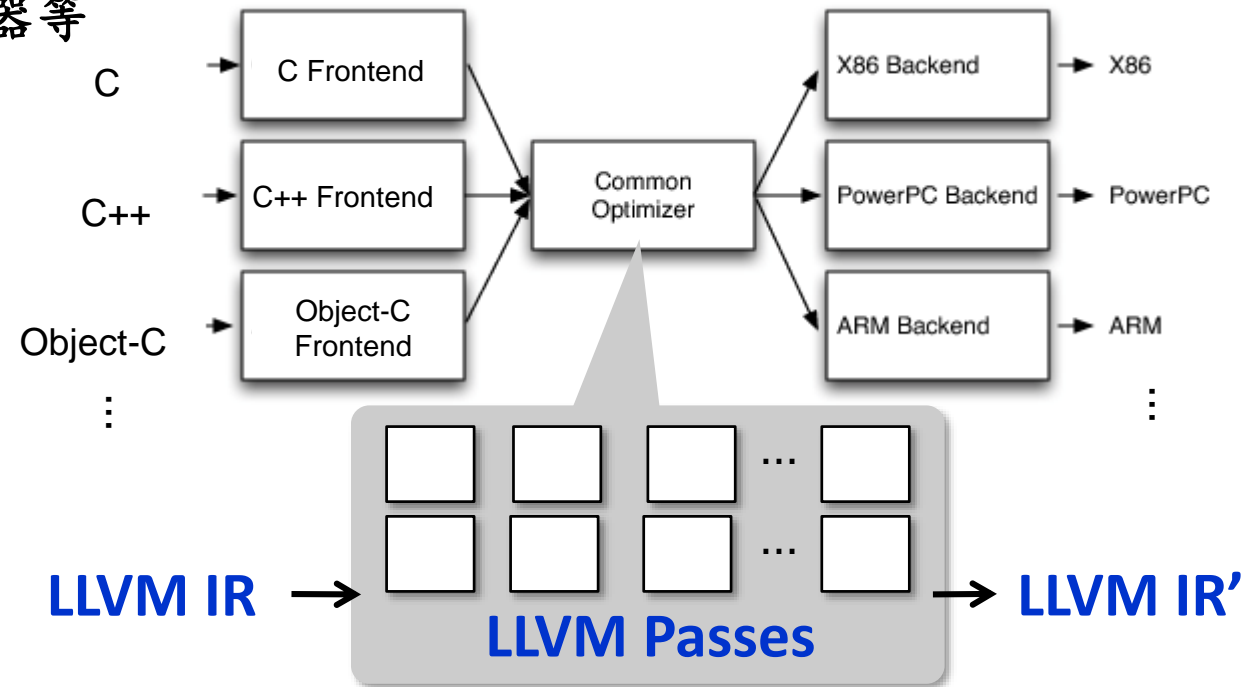
```

通过 `getelementptr(gep)`
 获取元素 `A[i]` 的地址
`inbounds` 表示 `i` 超出 10 (`%11`),
 则 `gep` 返回 `poison value`



□ LLVM提供108+ Passes <http://llvm.org/docs/Passes.html>

- 分析器：别名分析、调用图构造、依赖分析等
- 转换器：死代码消除、常量折叠、循环展开、循环分裂等
- 过程间优化器：函数内联、全局变量优化等
- 实用组件：CFG viewer、基本块提取器等





□ 编译器组织成一系列的passes

- 每个pass是一个分析或变换

□ Pass的类型

- **ModulePass**: general interprocedural pass
- **CallGraphSCCPass**: bottom-up on the call graph
- **FunctionPass**: process a function at a time
- **LoopPass**: process a natural loop at a time
- **BasicBlockPass**: process a basic block at a time

SCC 强连通分量

□ 施加的约束 (e.g. FunctionPass):

- FunctionPass 只能查看当前函数
- 不能维护跨函数之间的状态



中国科学技术大学
University of Science and Technology of China

下期预告：中间代码生成