COMP130014 编译

第十一讲：指令选择

徐 辉

xuh@fudan.edu.cn

大纲

一、AArch64指令集

二、phi指令处理

三、指令选择问题

一、AArch64指令集

指令集架构

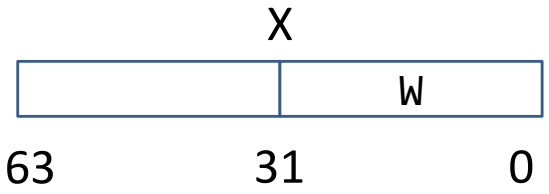
- 精简指令集（RISC）
  - 每条指令只做一件事（主要指内存访问和运算分离）
  - AArch/ARM、RISC-V
- 复杂指令集（CISC）
  - 一条指令可以包含多个底层操作（load-add-store）
  - X86（Intel IA-32）、X86-64架构（AMD64）
- 其它
  - VLIW：Very long instruction word (Intel IA-64)
  - EPIC：Explicitly parallel instruction computing

目标指令集：ARM v8a

- 32位版本：ARM Cortex-A32
- 32/64位版本：ARM Cortex-A57/A72/A73等，代表芯片
  - Apple A8/A8x/A9/A9x/A10/A10x（iPhone, iPad）
  - Apple M1/M2（iPhone, iPad, MacBook）
  - Qualcomm Kryo: 骁龙（Snapdragon 820）
- AArch64 vs ARM64 (Apple版本)

ARM-v8A寄存器：通用寄存器

- 通用寄存器：X0 - X30 (64-bit)
  - W0-W30：低32位




```
mov x1, 5
mov x2, 10
add x0, x1, x2
```

```
x1 = 5
x2 = 10
x0 = x1 + x2
```

```
mov w1, 5
mov w2, 10
add w0, w1, w2
```

```
w1 = 5
w2 = 10
w0 = w1 + w2
```

IR=>Assembly：数据存取

- 栈（顶）寄存器：SP（16字节对齐）

```
%x = alloca i32
store i32 1, i32* %x
%x0 = load i32, i32* %x
```

```
sub sp, sp, 16
mov w0, 1
str w0, [sp]
ldr w0, [sp]
```

sp = sp - 16

```
#: llc -O0 -march=arm64 -filetype=asm foo.ll –o foo.s
```

在MacOS (M1)上编译和运行

```
#: as foo.s –o foo.o
#: ld foo.o -lSystem -syslibroot `xcrun -sdk macosx --show-sdk-
path` -e _start -arch arm64
```

或

```
#: gcc test.o -e _main -arch arm64
```

在x86上运行编译和运行ARM-v8A程序

安装qemu工具链

```
#: sudo apt install qemu qemu-system qemu-user
#: sudo apt install gcc-aarch64-linux-gnu
#: sudo apt install qemu-user-static libc6-arm64-cross
```

交叉编译程序

```
#: aarch64-linux-gnu-gcc hello.c
```

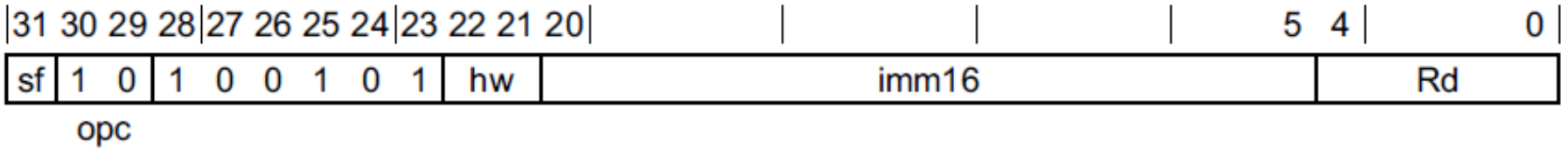
在虚拟机上运行程序

```
#: qemu-aarch64 -L /usr/aarch64-linux-gnu a.out
```

ARM-v8A指令：MOV

- MOV：任意16位立即数，或左移16/32/48位

```
MOV <Wd>, #<imm>
```



<imm>	For the 32-bit variant: is a 32-bit immediate which can be encoded in "imm16:hw". For the 64-bit variant: is a 64-bit immediate which can be encoded in "imm16:hw".
<shift>	For the 32-bit variant: is the amount by which to shift the immediate left, either 0 (the default) or 16, encoded in the "hw" field as <shift>/16. For the 64-bit variant: is the amount by which to shift the immediate left, either 0 (the default), 16, 32 or 48, encoded in the "hw" field as <shift>/16.

```
mov x1, 65535
mov x2, 65539
mov x3, 131070
```

```
mov x8, 3
movk x8, 1, lsl 16
```

ARM-v8A指令：寻址模式

- 不支持直接寻址，间接寻址

Addressing Mode	Offset		
	Immediate	Register	Extended Register
Base register only (no offset)	[base{, #0}]	-	-
Base plus offset	[base{, #imm}]	[base, Xm{, LSL #imm}]	[base, Wm, (S|U)XT(X|W) {#imm}]
Pre-indexed	[base, #imm]!	-	-
Post-indexed	[base], #imm	[base], Xm[a]	-
Literal (PC-relative)	label	-	-

```
ldr x2, [x1]
ldr x2, [x1, 10]
ldr x2, [x1, x0]
ldr x2, [x1, 10]!
ldr x2, [x1], 10
ldr x2, [x1, x0, lsl 3]
```

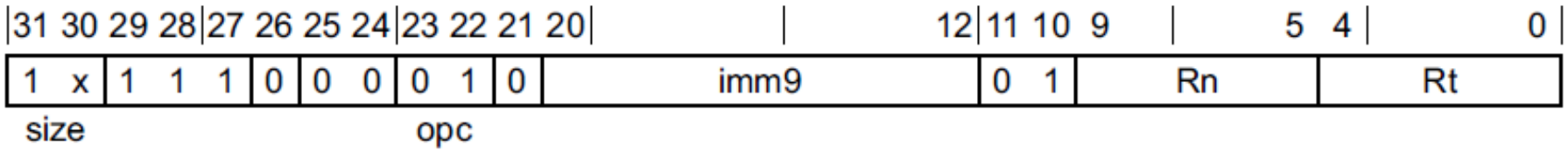
```
x2 = [x1 + 10]
x2 = [x1 + x0]
x1 = x1 + 10, x2 = [x1]
x2 = [x1], x1 = x1 + 10
x2 = [x1 + x0 * 8]
```

```
str w0, [x1]
str w0, [x1, 10]
str x2, [x1, x0]
```

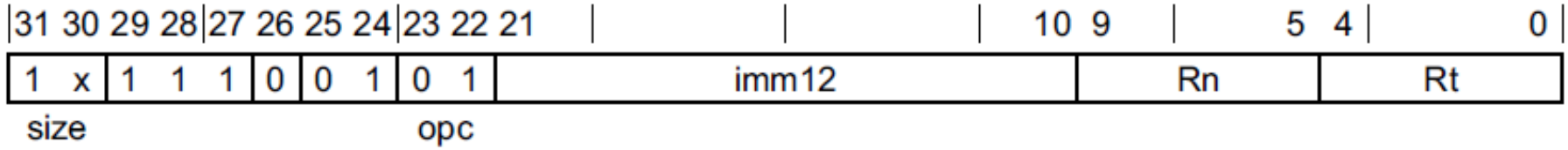
ARM-v8A指令：LDR（立即数）

```
ldr x2, [x1]
ldr x2, [x1, 10]
ldr x2, [x1, 10]!
```

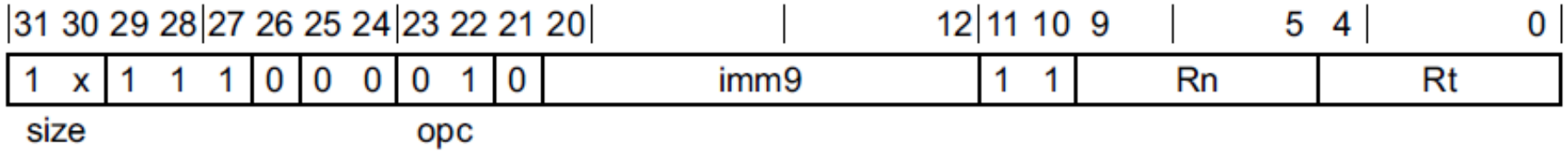
```
LDR <Xt>, [<Xn|SP>], #<simm>
```




```
LDR <Xt>, [<Xn|SP>{, #<pimm>}]
```




```
LDR <Xt>, [<Xn|SP>, #<simm>]!
```



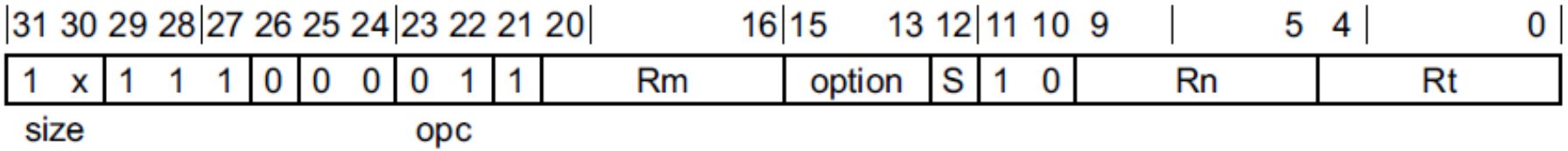
<simm> Is the signed immediate byte offset, in the range -256 to 255, encoded in the "imm9" field.

<pimm> For the 32-bit variant: is the optional positive immediate byte offset, a multiple of 4 in the range 0 to 16380, defaulting to 0 and encoded in the "imm12" field as <pimm>/4.

For the 64-bit variant: is the optional positive immediate byte offset, a multiple of 8 in the range 0 to 32760, defaulting to 0 and encoded in the "imm12" field as <pimm>/8.

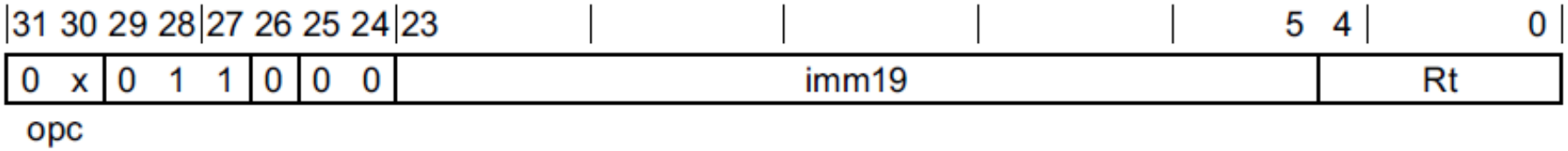
ARM-v8A指令：LDR（寄存器/标签）

```
LDR <Xt>, [<Xn|SP>, (<Wm>|<Xm>){, <extend> {<amount>}}]
```




```
ldr x2, [x1, x0]
ldr x2, [x1, x0, lsl 3]
```

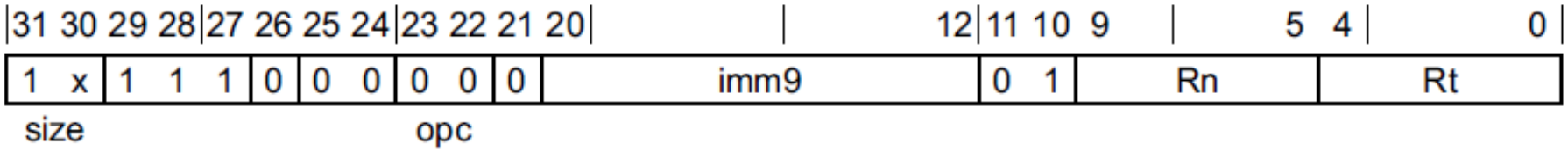
```
LDR <Xt>, <label>
```



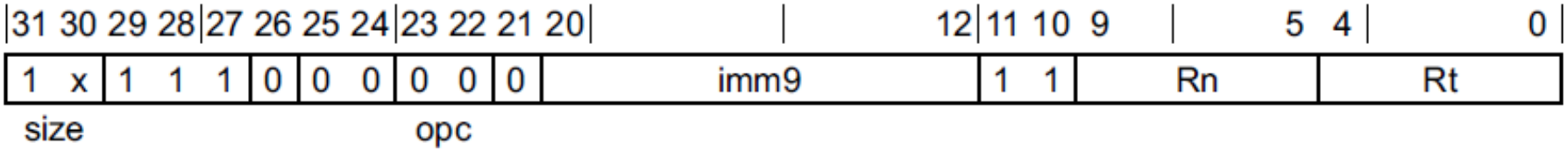
<label> Is the program label from which the data is to be loaded. Its offset from the address of this instruction, in the range +/-1MB, is encoded as "imm19" times 4.

ARM-v8A指令：STR

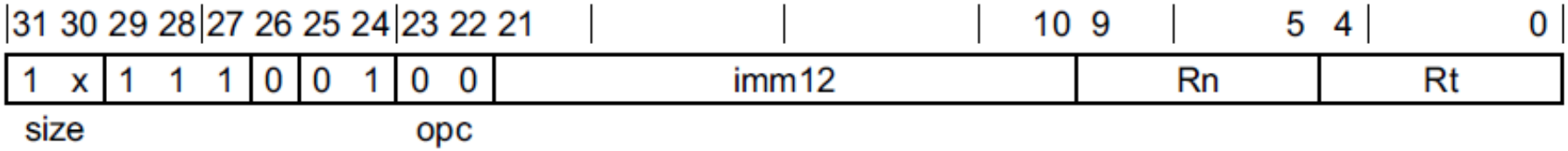
```
STR <Wt>, [<Xn|SP>], #<simm>
```



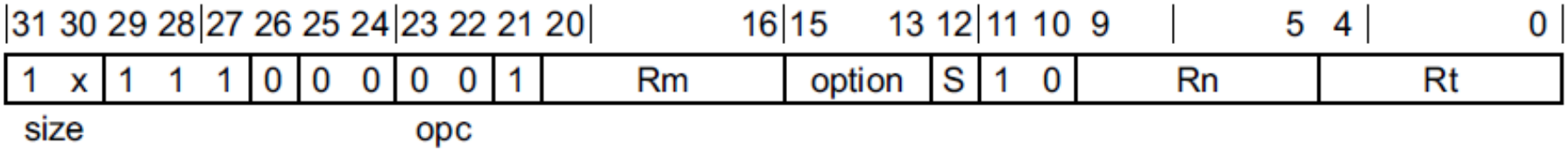

```
STR <Xt>, [<Xn|SP>, #<simm>]!
```




```
STR <Xt>, [<Xn|SP>{, #<pimm>}]
```




```
STR <Xt>, [<Xn|SP>, (<Wm>|<Xm>){, <extend> {<amount>}}]
```



复合类型如何翻译？

```
define i32 @main() {
  %1 = alloca [2 x i32]
  %2 = getelementptr [2 x i32], [2 x i32]* %1, i32 0, i32 0
  store i32 99, i32* %2
  %3 = load i32, i32* %2
  ret i32 %3
}
```

```
%mystruct = type { i32, i32 }
define i32 @main() {
  %1 = alloca %mystruct
  %2 = getelementptr %mystruct, %mystruct* %1, i32 0, i32 0
  store i32 1, i32* %2
  ret i32 0
}
```

IR=>Assembly：算数运算

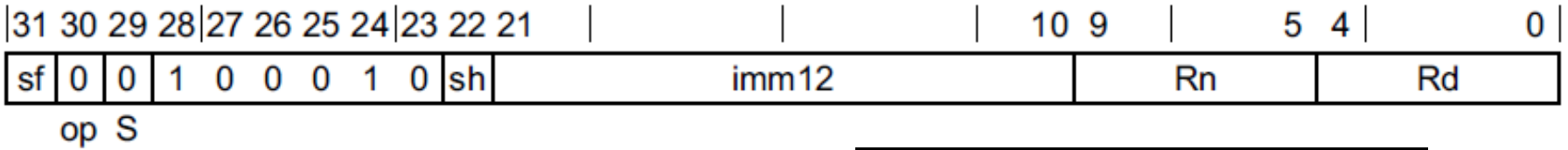
```
%r1 = add i32 %0, %1
%r2 = sub i32 %r1, 2
%r3 = mul i32 %r2, %1
%r4 = sdiv i32 %r3, %1
```

```
add  w8, w0, w1
sub  w8, w8, 2
mul  w8, w8, w1
sdiv w0, w8, w1
```

ARM-v8A指令：算数运算：ADD

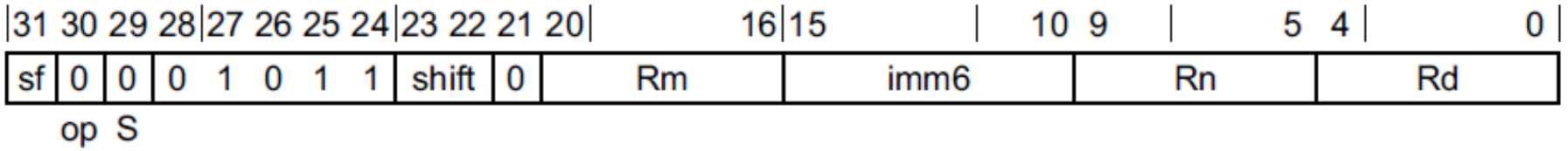
```
ADD <Xd|SP>, <Xn|SP>, #<imm>{, <shift>}
```

sh == 1，imm左移12位




```
add x0, x1, 4095
add x0, x1, 4097
add x0, x1, 20480
```

```
ADD <Xd>, <Xn>, <Xm>{, <shift> #<amount>}
```

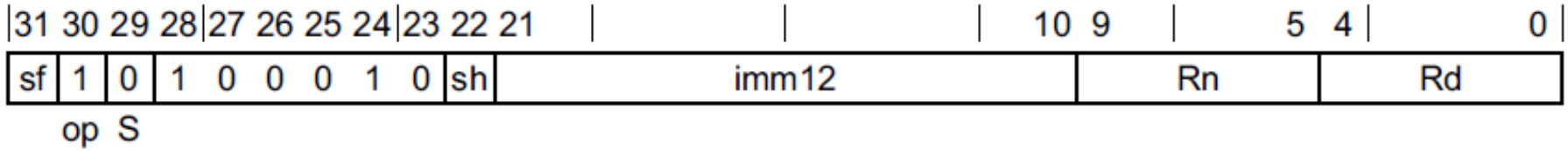



```
add x0, x1, x2
```

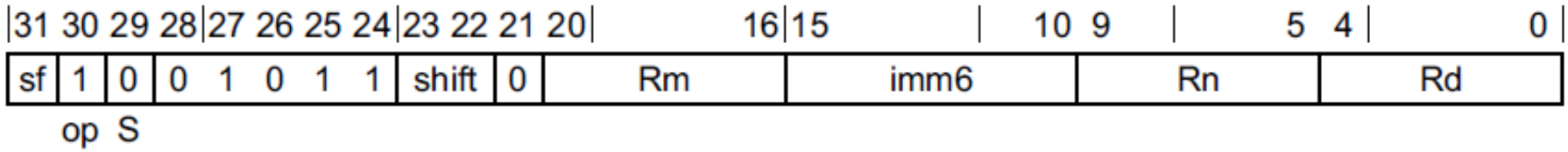
For the 64-bit variant: is the shift amount, in the range 0 to 63, defaulting to 0 and encoded in the "imm6" field.

ARM-v8A指令：算数运算：SUB

```
SUB <Xd|SP>, <Xn|SP>, #<imm>{, <shift>}
```



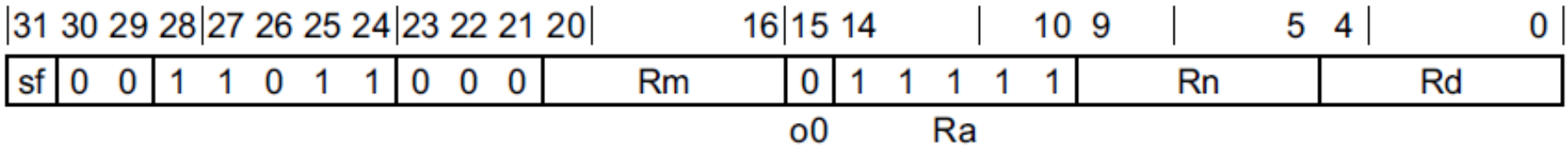

```
SUB <Xd>, <Xn>, <Xm>{, <shift> #<amount>}
```



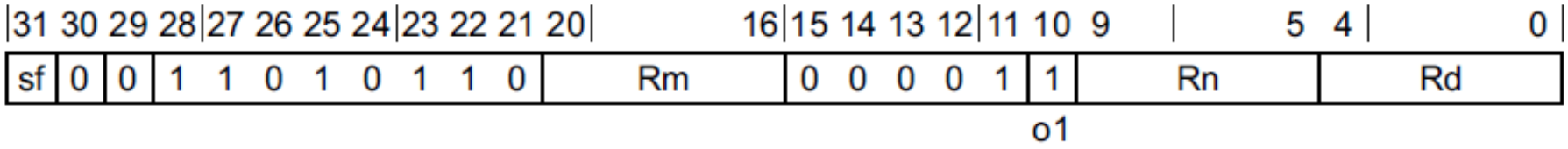
ARM-v8A指令：算数运算：MUL/SDIV

```
MUL <Xd>, <Xn>, <Xm>
```

不支持立即数

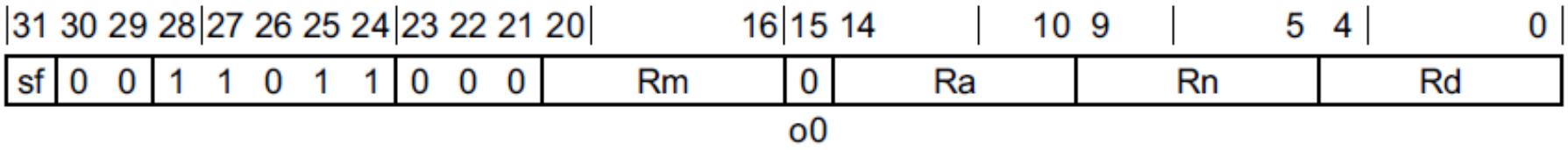



```
SDIV <Xd>, <Xn>, <Xm>
```

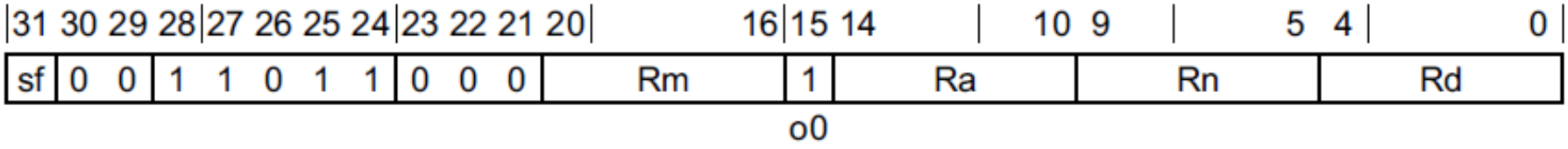


ARM-v8A指令：复合算数运算

MADD <Xd>, <Xn>, <Xm>, <Xa>



MSUB <Xd>, <Xn>, <Xm>, <Xa>




```
madd x0, x1, x2, x3
msub x0, x1, x2, x3
```

```
x0 = x1 * x2 + x3
x0 = x1 * x2 - x3
```

IR=>Assembly：比较运算和结果获取

```
%r1 = icmp sgt i32 %0, %1
%r2 = zext i1 %r1 to i32
```

```
cmp  w0, w1
cset w0, gt
```

条件

```
%r1 = icmp sge i32 %0, %1
%r2 = zext i1 %r1 to i32
```

```
cmp  w0, w1
cset w0, ge
```

```
%r1 = icmp eq i32 %0, %1
%r2 = zext i1 %r1 to i32
```

```
cmp  w0, w1
cset w0, eq
```

```
%r1 = icmp ne i32 %0, %1
%r2 = zext i1 %r1 to i32
```

```
cmp  w0, w1
cset w0, ne
```

```
%r1 = icmp sle i32 %0, %1
%r2 = zext i1 %r1 to i32
```

```
cmp  w0, w1
cset w0, le
```

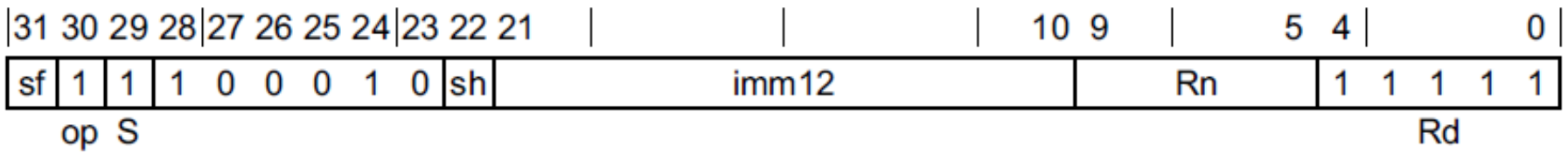
```
%r1 = icmp lt i32 %0, %1
%r2 = zext i1 %r1 to i32
```

```
cmp  w0, w1
cset w0, lt
```

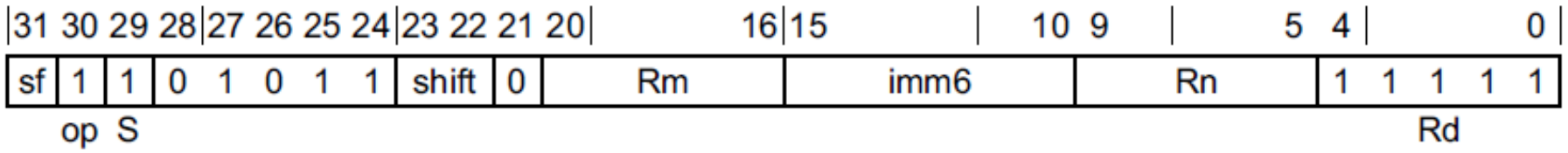
ARM-v8A指令：比较运算：CMP

- 基于PSR（NZCV）寄存器实现

CMP <Xn|SP>, #<imm>{, <shift>}　　SUBS WZR, <Wn|WSP>, #<imm> {, <shift>}



CMP <Wn>, <Wm>{, <shift> #<amount>}



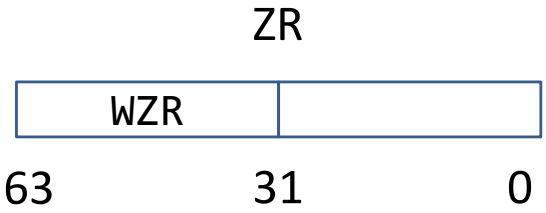
ARM-v8A指令：读取NZCV

- 基于减法实现，更新CPSR寄存器：
  - N（31位）：符号标志位；如果负，则N=1
  - Z（30位）：0标志位；如果0，则Z=1
  - C（29位）：进位标志位；
    - 无符号数：加法进位，或减法不借位，则C=1
  - V（28位）：溢出标志位；有符号运算溢出，则V=1

Result	N	Z	C	V
Greater than	0	0	1	0
Less than	1	0	0	0
Equal	0	1	1	0

```
mrs x0, nzcv
```

ARM-v8A寄存器：零寄存器

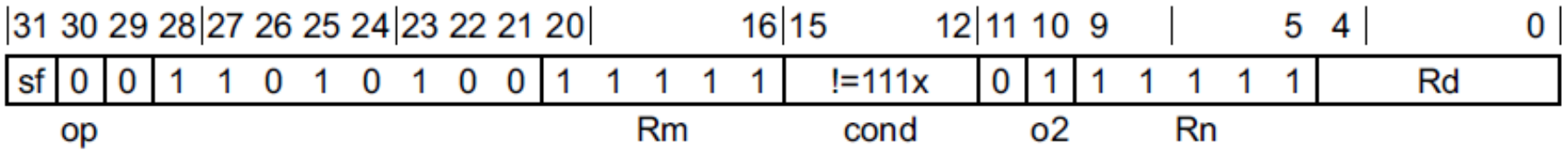



```
mov x1, xzr
mov w1, wzr
```

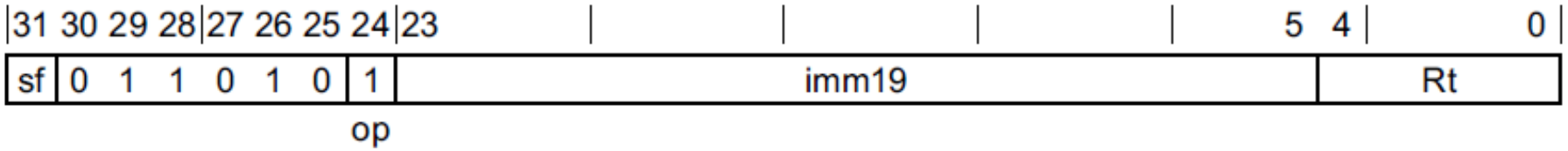
```
x1 = 0
w2 = 0
```

ARM v8a指令：条件指令（举例）

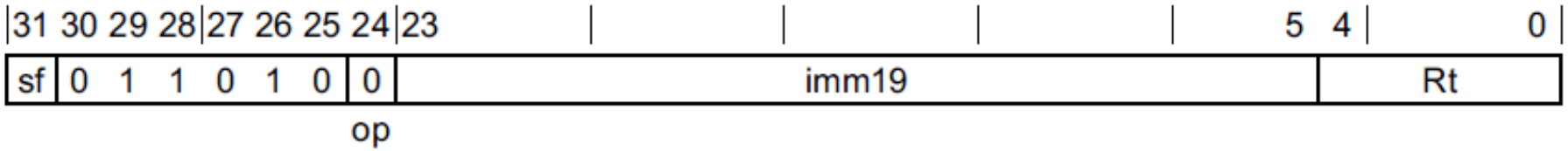
```
CSET <Xd>, <cond>
```




```
CBNZ <Xt>, <label>
```




```
CBZ <Xt>, <label>
```



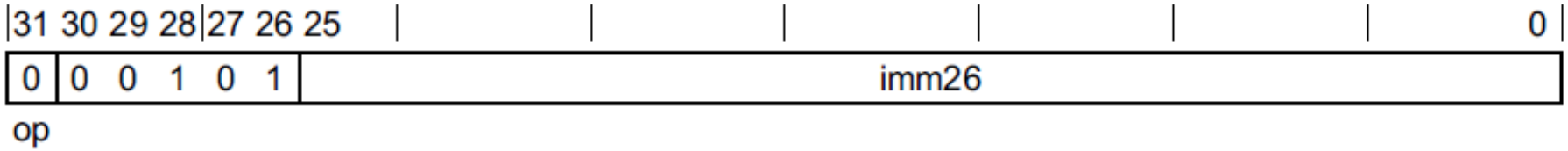
IR=>Assembly：跳转语句

```
bb0:
  %r1 = icmp sgt i32 %0, %1
  br i1 %r1, label %bb1, label %bb2
bb1:
  br label %bb3
bb2:
  br label %bb3
bb3:
```

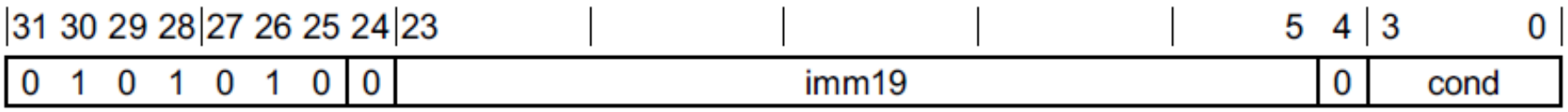
```
cmp     w0, w1
b.le    .LBB0_2
b       .LBB0_3
.LBB0_2:
.LBB0_3:
```

ARM-v8A指令：跳转指令

B <label>



B.<cond> <label>



Mnemonic	Instruction	Branch offset range from the PC
B.cond	Branch conditionally	±1MB
BC.cond	Branch Consistent conditionally	±1MB
CBNZ	Compare and branch if nonzero	±1MB
CBZ	Compare and branch if zero	±1MB
TBNZ	Test bit and branch if nonzero	±32KB
TBZ	Test bit and branch if zero	±32KB

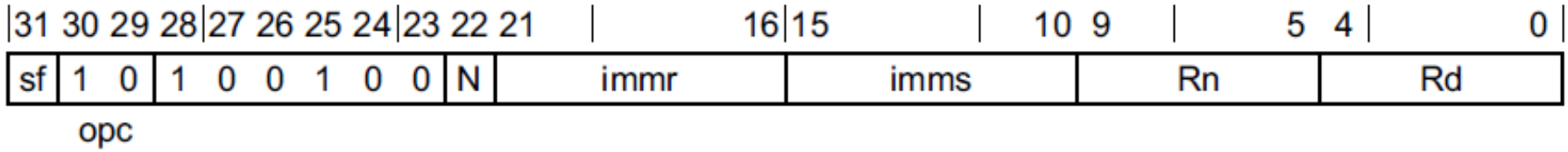
```
add w0, w1, w2
cbz zero_set
...
zero_set:
```

IR=>Assembly：异或运算（逻辑NOT）

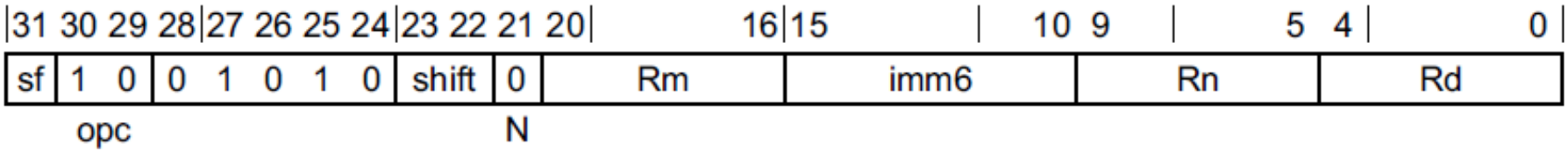
```
%r2 = xor i1 %r1, 0
```

```
eor  w0, w0, 1
```

EOR <Xd|SP>, <Xn>, #<imm>



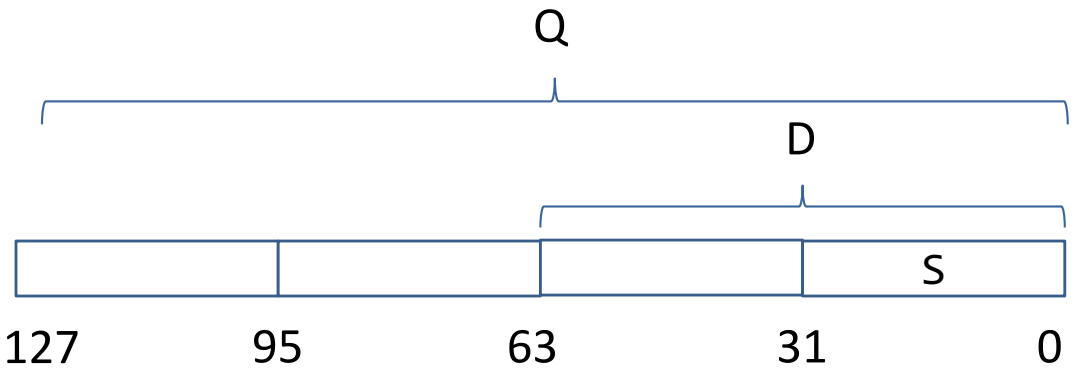
EOR <Xd>, <Xn>, <Xm>{, <shift> #<amount>}



Mnemonic	Instruction
AND	Bitwise AND
ANDS	Bitwise AND and set flags
EOR	Bitwise exclusive OR
ORR	Bitwise inclusive OR
TST	Test bits

向量寄存器和SIMD指令

- 向量寄存器：Q0-Q31




```
VLDR S0, [X0]
VLDR S1, [X1]
VADD.F32 S2, S0, S1
```

浮点数运算

```
VLDR Q0, [X0]
VLDR Q1, [X1]
VADD.I32 Q2, Q0, Q1
```

向量运算

IR=>Assembly：函数

```
@g = global i32 10

define i32 @foo(i32 %0) {
   %x = alloca i32
   store i32 %0, i32* %x
   %g0 = load i32, i32* @g
   ret i32 %g0
}

define i32 @main() {
  %r0 = call i32 @foo(i32 1)
  ret i32 %r0;
}
```

```
foo:
    sub     sp, sp, 16
    adrp    x8, g
    add     x8, x8, :lo12:g
    str     w0, [sp, 12]
    ldr     w0, [x8]
    add     sp, sp, 16
    ret
main:
    str     x30, [sp, -16]!
    mov     w0, #1
    bl      foo
    ldr     x30, [sp], 16
    ret
g:
    .word   10
```

1 word = 4 byte

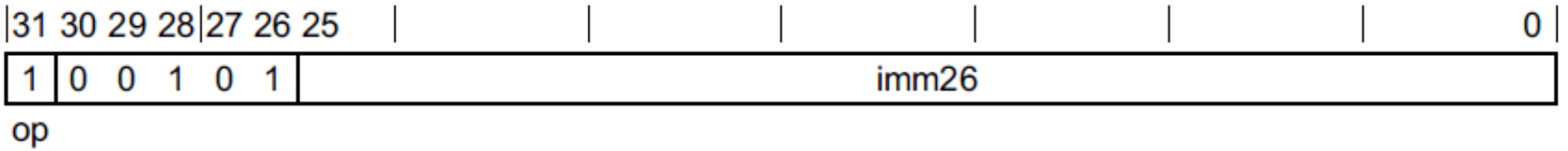
调用规约

- 参数传递: X0-X7
- 返回值: X0-X1
- Caller-saved Registers: X9-X15 （临时寄存器）
- Callee-saved Registers: X19-X28
- X29：一般用于栈帧基指针
- X30：一般用于返回地址
- SP：栈顶指针

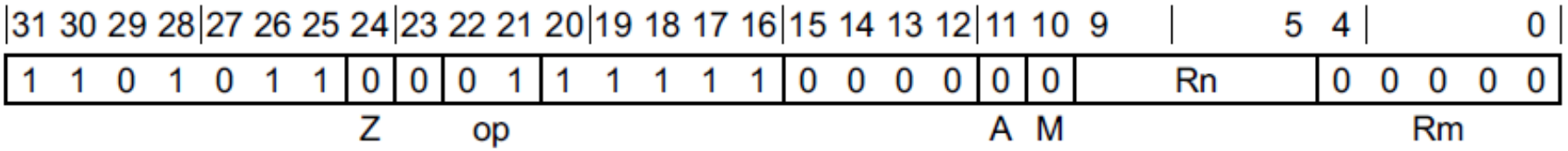
ARM-v8A指令：函数调用

- 跳转并将X30设置为PC+4

```
BL <label>
```




```
BLR <Xn>
```



IR=>Assembly：取址（全局变量）

Mnemonic	Instruction
ADRP	Compute address of 4KB page at a PC-relative offset
ADR	Compute address of label at a PC-relative offset.

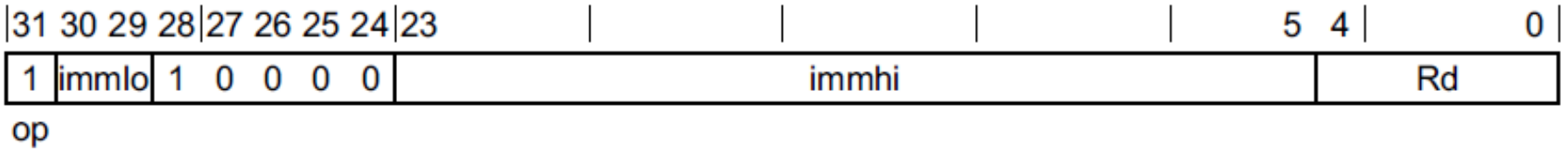
4KB对齐：末尾12位为0

```
adrp  x8, g
add   x8, x8, :lo12:g
```

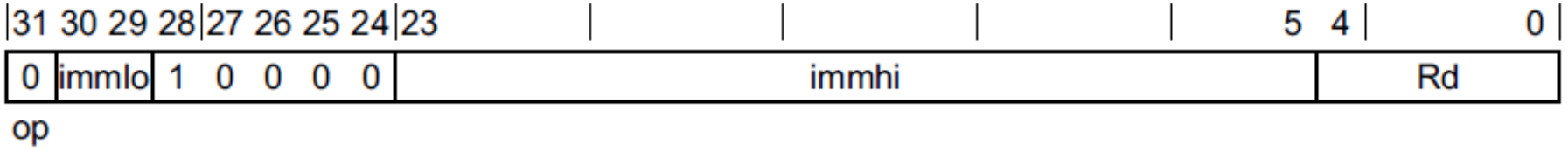
或：

```
adrp    x8, g@PAGE
add     x8, x8, g@PAGEOFF
```

ADRP <Xd>, <label>



ADR <Xd>, <label>



二、phi指令处理

phi指令的引入

```
if(a==0) {
    a = a + b;
}
let r = a + c;
```

```
bb1:
    %r1 = icmp eq i32 %a1, 0
    br i1 %r1, label %bb2, label %bb3
bb2:
    %a2 = add i32 %a1, %b1
    br label %bb2
bb3:
    %a3 = phi i1 [%a1, %bb1], [%a2, %bb2]
    %r1 = add i32 %a3, %b1
```

消除phi指令方式一：还原store-load

```
bb1:
    %a = alloca i32
    %r1 = icmp eq i32 %a1, 0
    store i32 %a1, i32* %a
    br i1 %r1, label %bb2, label %bb3
bb2:
    %a2 = add i32 %a1, %b1
    store i32 %a2, i32* %a
    br label %bb2
bb3:
    %a3 = load i32, i32* %a
    %r1 = add i32 %a3, %b1
```

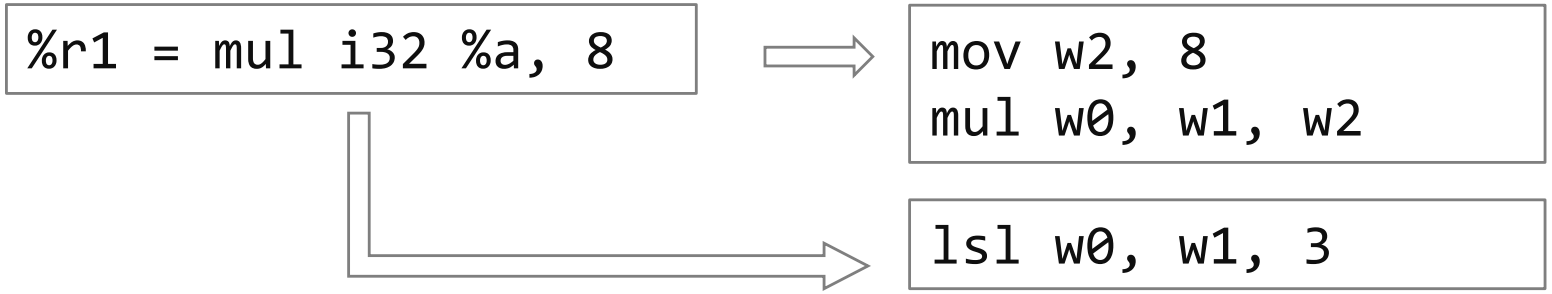
消除phi指令方式二：使用伪指令

```
bb1:
    %r1 = icmp eq i32 %a1, 0
    %a3 = %a1
    br i1 %r1, label %bb2, label %bb3
bb2:
    %a2 = add i32 %a1, %b1
    %a3 = %a2
    br label %bb2
bb3:
    %a3 = phi i1 [%a1, %bb1], [%a2, %bb2]
    %r1 = add i32 %a3, %b1
```

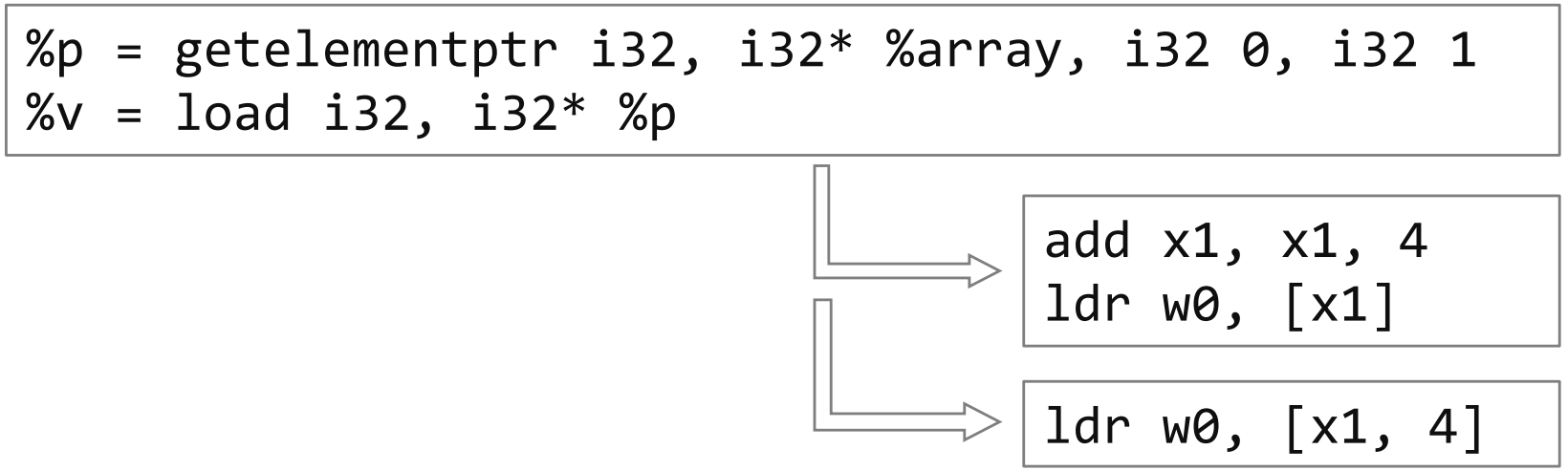
三、指令选择问题

IR指令存在多种ASM翻译方式

一条IR指令，多种ASM翻译方式



IR指令组合，多种ASM翻译方式

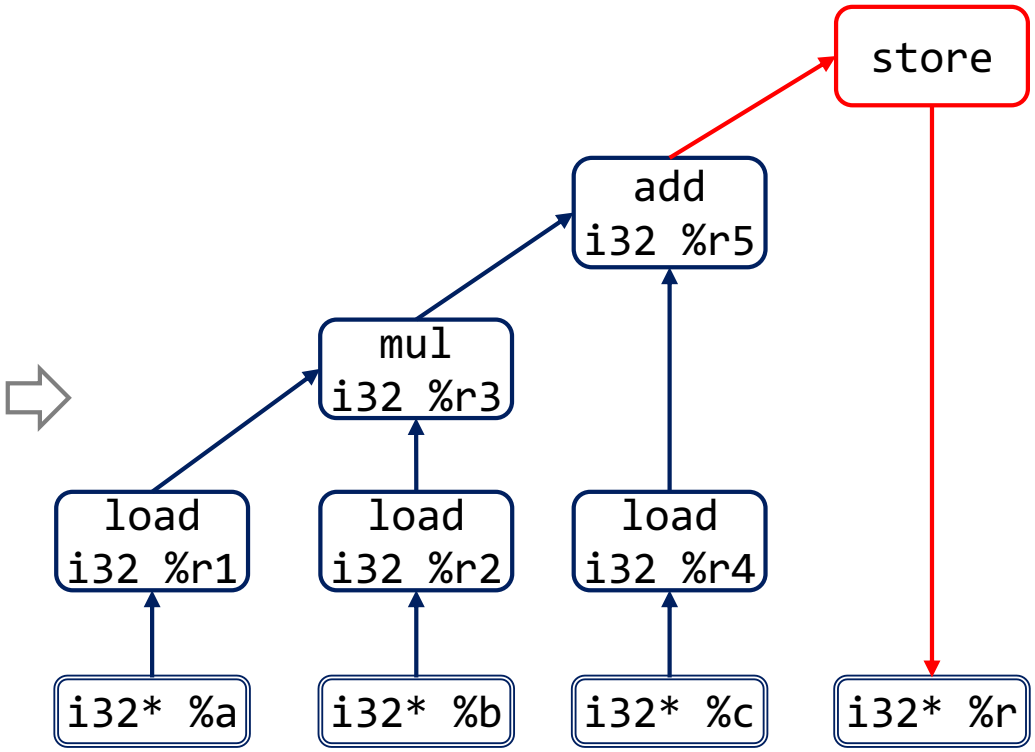


IR=>指令选择图

- 特点：有向无环图

```
r = a * b + c;
```

```
%r1 = load i32 %a;
%r2 = load i32 %b;
%r3 = mul i32 %r1, %r2;
%r4 = load i32 %c;
%r5 = add i32 %r3, %r4;
store i32 %r5, %r;
```

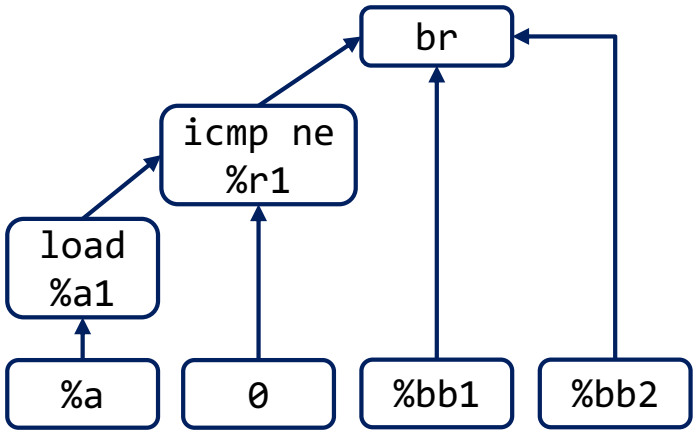


指令选择图

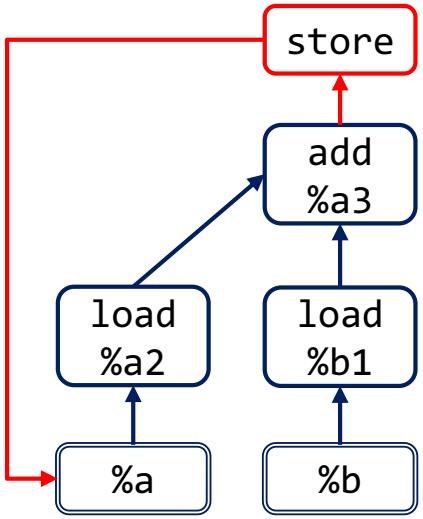
每个代码块一个DAG

```
if(a==0) {
    a = a + b;
}
let r = a + c;
```

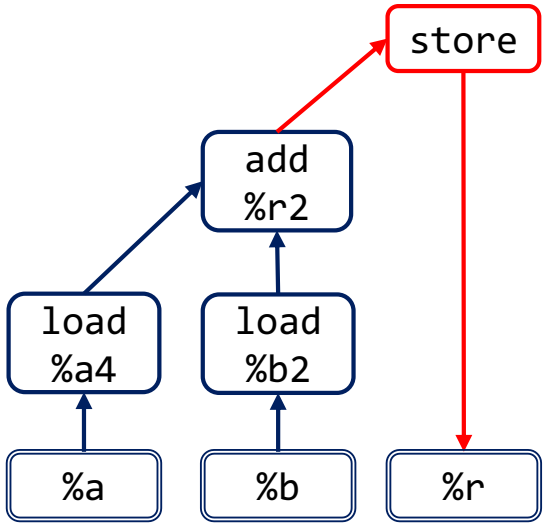
```
bb1:
    %a1 = load i32, i32* %a
    %r1 = icmp eq i32 %a1, 0
    br i1 %r1, label %bb2,
               label %bb3
bb2:
    %a2 = load i32, i32* %a
    %b1 = load i32, i32* %b
    %a3 = add i32 %a2, %b1
    store i32 %a3, i32* %a
    br label %bb2
bb3:
    %a4 = load i32, i32* %a
    %b2 = load i32, i32* %b
    %r2 = add i32 %a4, %b2
    store i32 %r2, i32* %r
```



%bb1 指令选择图



%bb2 指令选择图

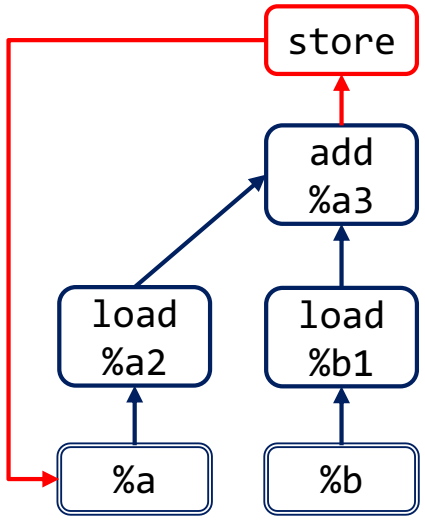


%bb3 指令选择图

指令选择图中出现环的情况：load-store

- SSA消除load-store后的指令选择图没有环
- 还原phi指令后可能引入环：一定先load，后store

```
%a2 = load i32, i32* %a
%b1 = load i32, i32* %b
%a3 = add i32 %a2, %b1
store i32 %a3, i32* %a
br label %bb2
```



%bb2 指令选择图

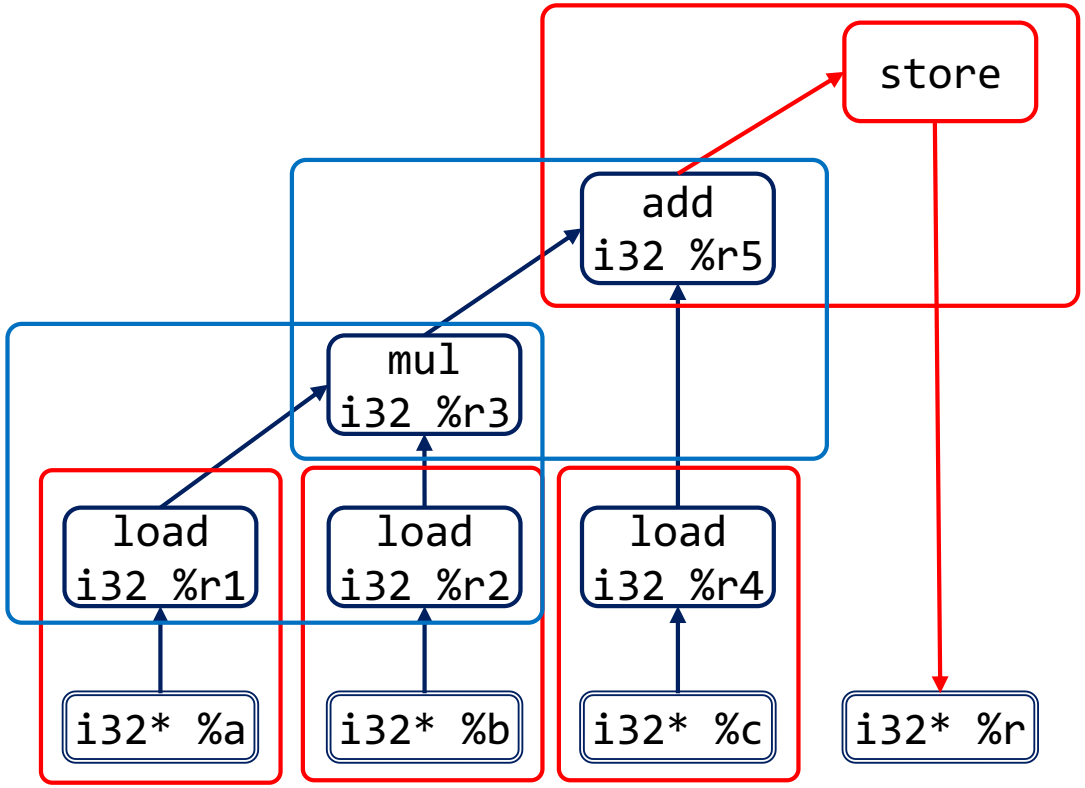
指令选择问题=>铺树问题

- 输入Selection DAG，如何铺树（图）使得最终的汇编代码：
  - 体积小（指令数少）
  - 运算快

指令	开销
LDR	4
STR	1
ADD/ADD	1
SUB/SUBS	1
MUL	3
MADD/MSUB	3
SDIV	4-20
MOV	1
ADR/ADRP	1
B/BL/RET	1
CBZ/TBZ...	1

指令运行开销假设
（Arm Cortex-A72）

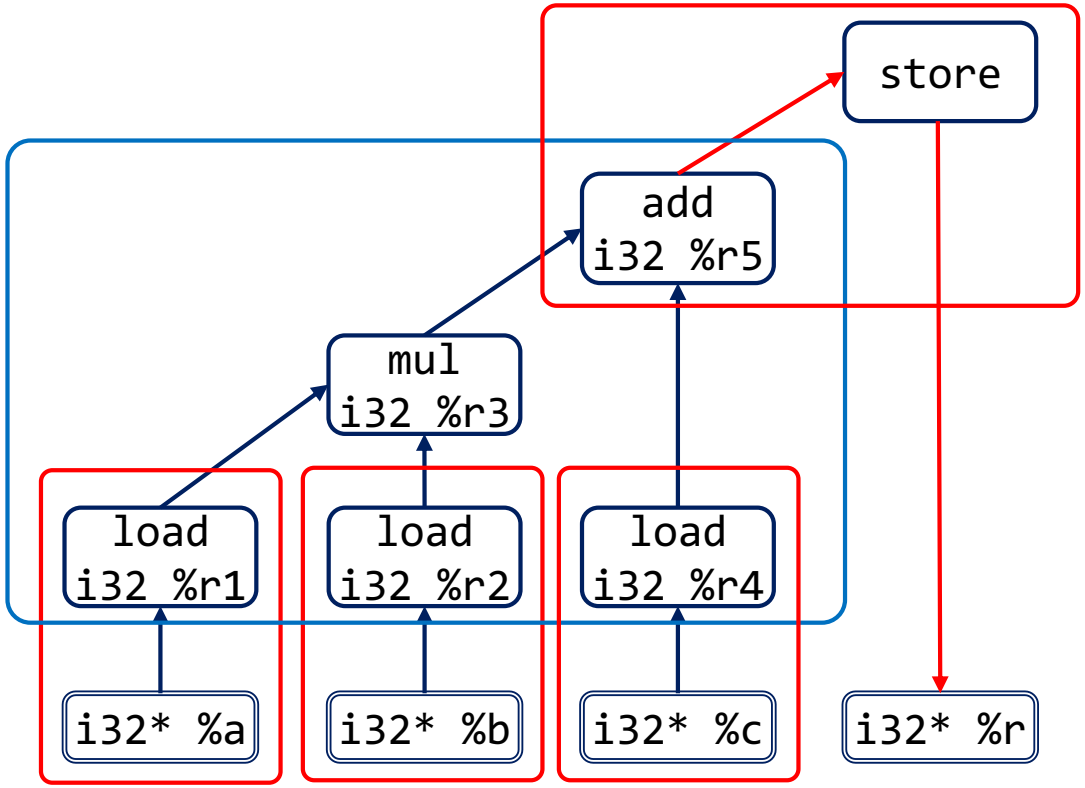
指令选择问题=>铺树问题




```
ldr %w1, [sp, #a]
ldr %w2, [sp, #b]
ldr %w3, [sp, #c]
mul %w3, %w1, %w2
add %w5, %w3, %w4
store %w5, [sp, #r]
```

方式一

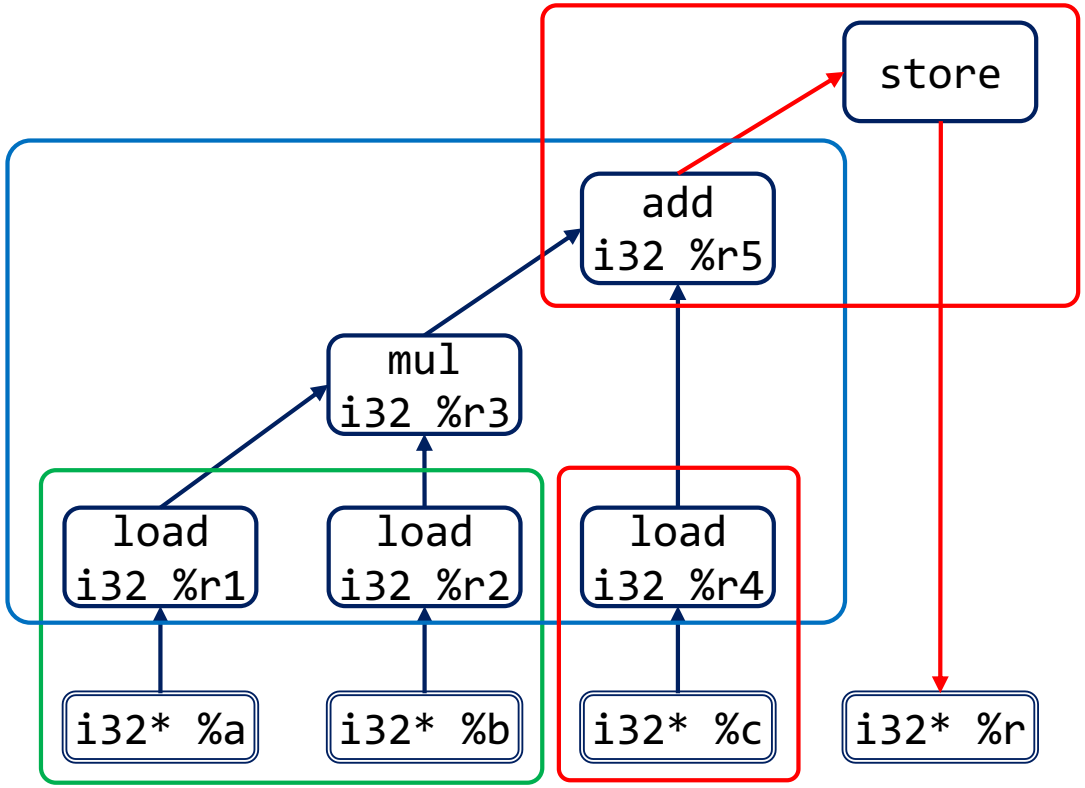
指令选择问题=>铺树问题




```
ldr %w1, [sp, #a]
ldr %w2, [sp, #b]
ldr %w4, [sp, #c]
madd %w5, %w1, %w2, %w4
store %w5, [sp, #r]
```

方式二

指令选择问题=>铺树问题

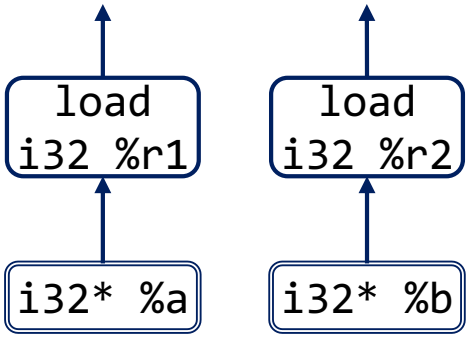



```
ldp %w1, %r2, [sp, #a]
ldr %w3, [sp, #c]
madd %w5, %w1, %w2, %r4
store %w5, [sp, #r]
```

方式三

load + load/store + store

- 假设a和b的地址连续

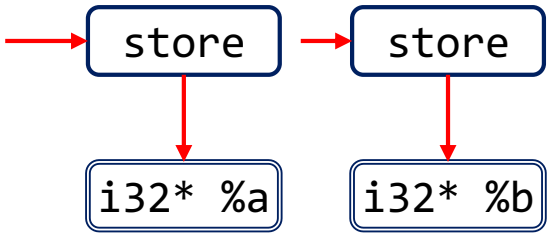



```
ldr %w1, [sp, .a]
ldr %w2, [sp, .b]
```

开销：8

```
ldp %w1, %w2, [sp, .a]
```

开销：4



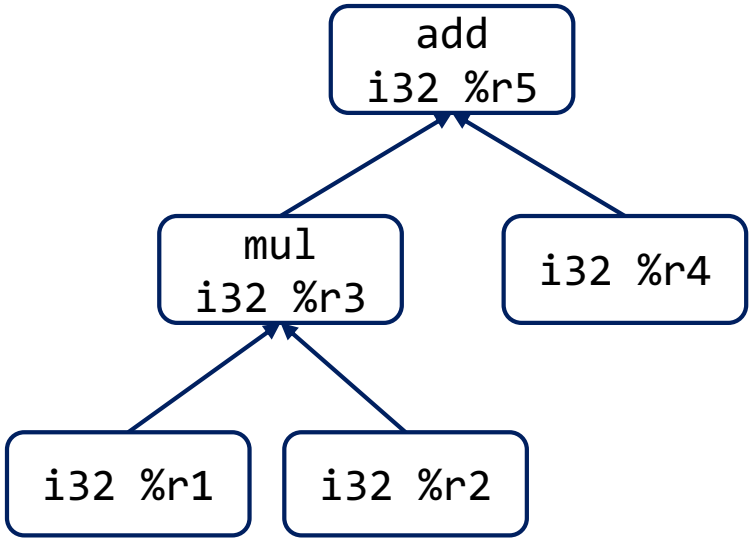

```
str %w1, [sp, .a]
str %w2, [sp, .b]
```

开销：2

```
stp %w1, %w2, [sp, .a]
```

开销：1

mul + add

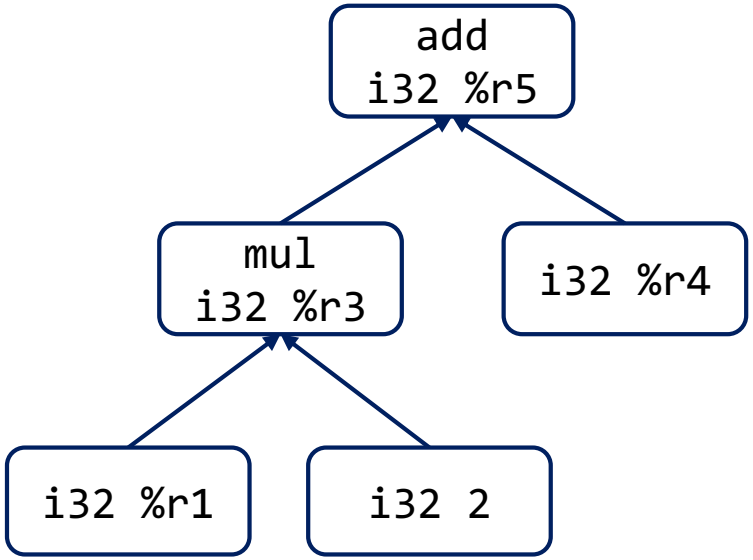



```
mul %w3, %w1, %w2
add %w5, %w3, %w4
```

开销：4

```
madd %w5, %w1, %w2, %w4
```

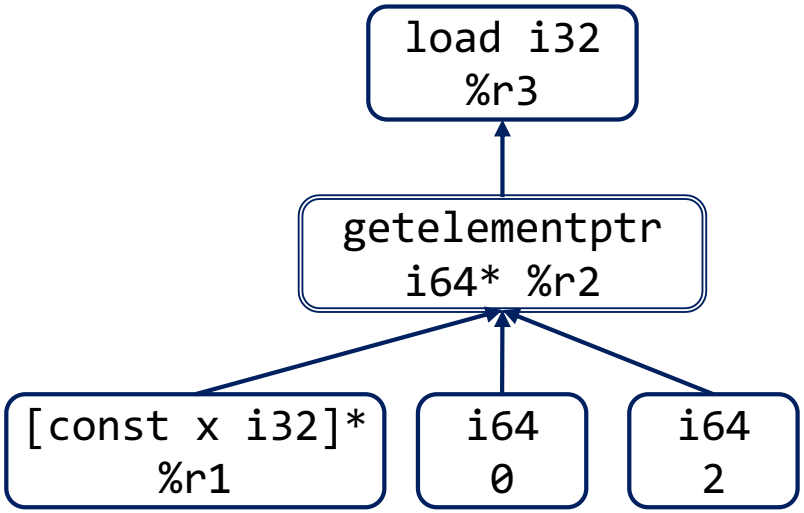
开销：3




```
mov %w0, 2
mul %w3, %w1, %w0
add %w5, %w3, %w4
```

开销：5

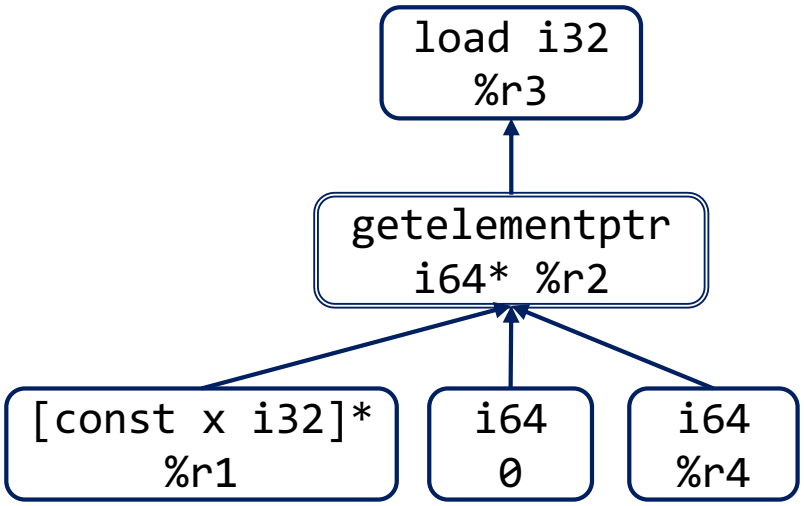
load + getelementptr：数组



常量索引

```
add %w2, %w1, 16
ldr %w3, [%w2]          开销：5
```

```
ldr %w3, [%w1, 16]      开销：4
```



变量索引

```
mov %w0, 8
mul %w2, %w4, %w0
add %w2, %w1, %w2
ldr %w3, [%w2]          开销：9
```

```
mov %w0, #8
mul %w2, %w4 ,%w0
ldr %w3, [%w1, %w2]     开销：8
```

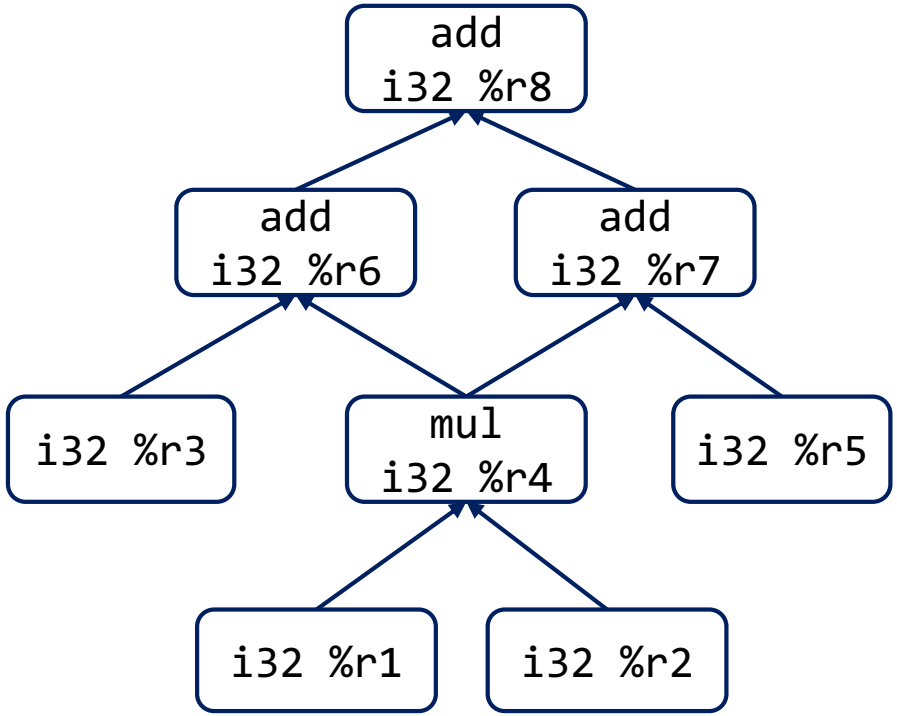
```
ldr %w3, [%w1, %w4, lsl 3]
```

开销：4

铺树问题解法

- 贪心算法：Maximal Munch
  - 每次选择覆盖节点最多、开销最低的规则
  - 拓扑排序：生成汇编指令
  - 局部最优
- 动态规划
  - 从树根开始，递归搜索每个节点的最优方案

贪心法不一定能得到最优解：mul + add




```
mul %r4, %r1, %r2
add %r6, %r3, %r4
add %r7, %r4, %r5
add %r8, %r6, %r7
```

开销：6

```
madd %r6, %r1, %r2, %r3
madd %r7, %r1, %r2, %r5
add %r8, %r6, %r7
```

开销：7

参考资料

- Arm® Architecture Reference Manual for A-profile architecture
- 在线模拟器：http://163.238.35.161/~zhangs/arm64simulator/