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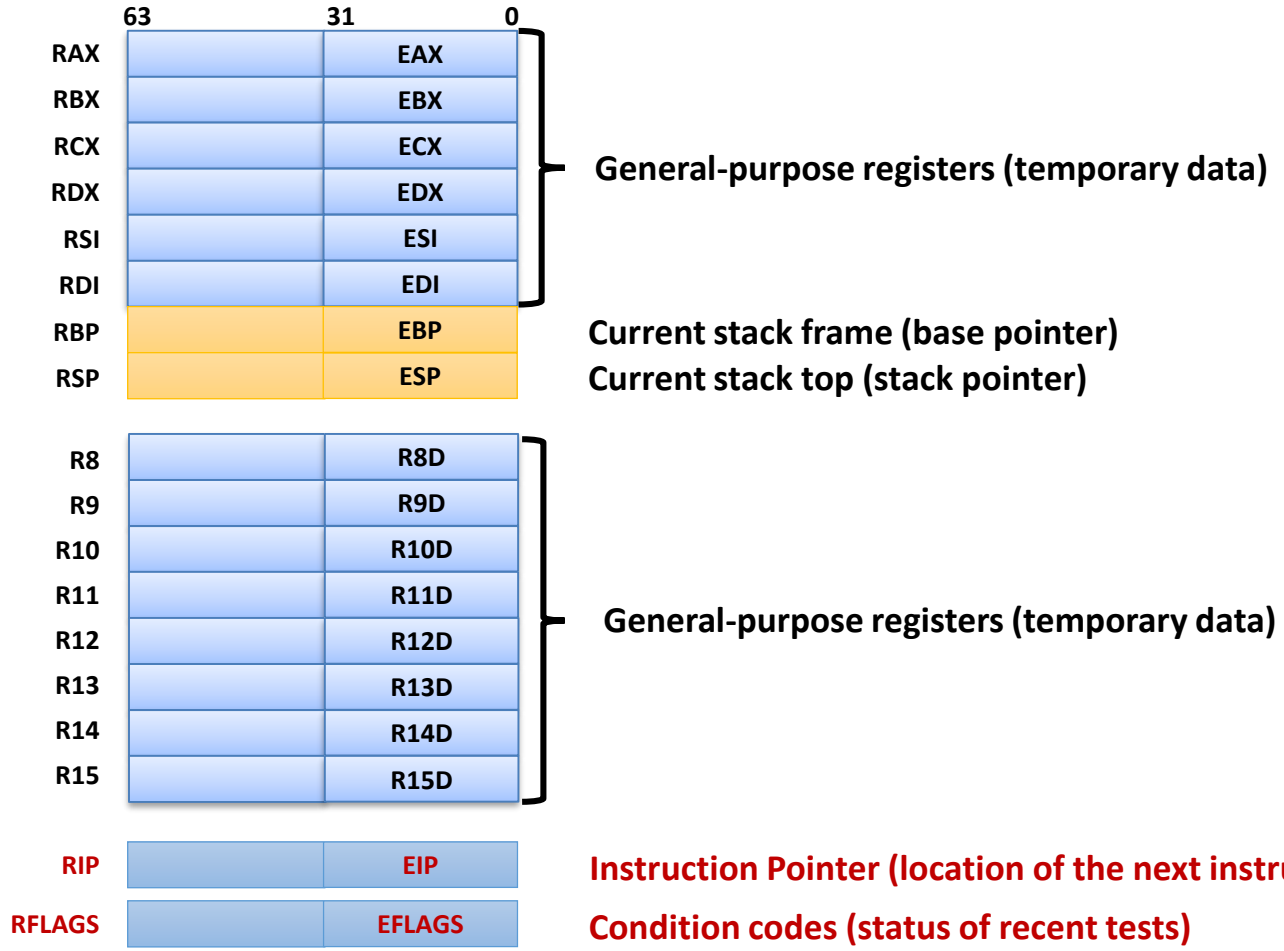
Fall 2018

Assembly II: Control Flow

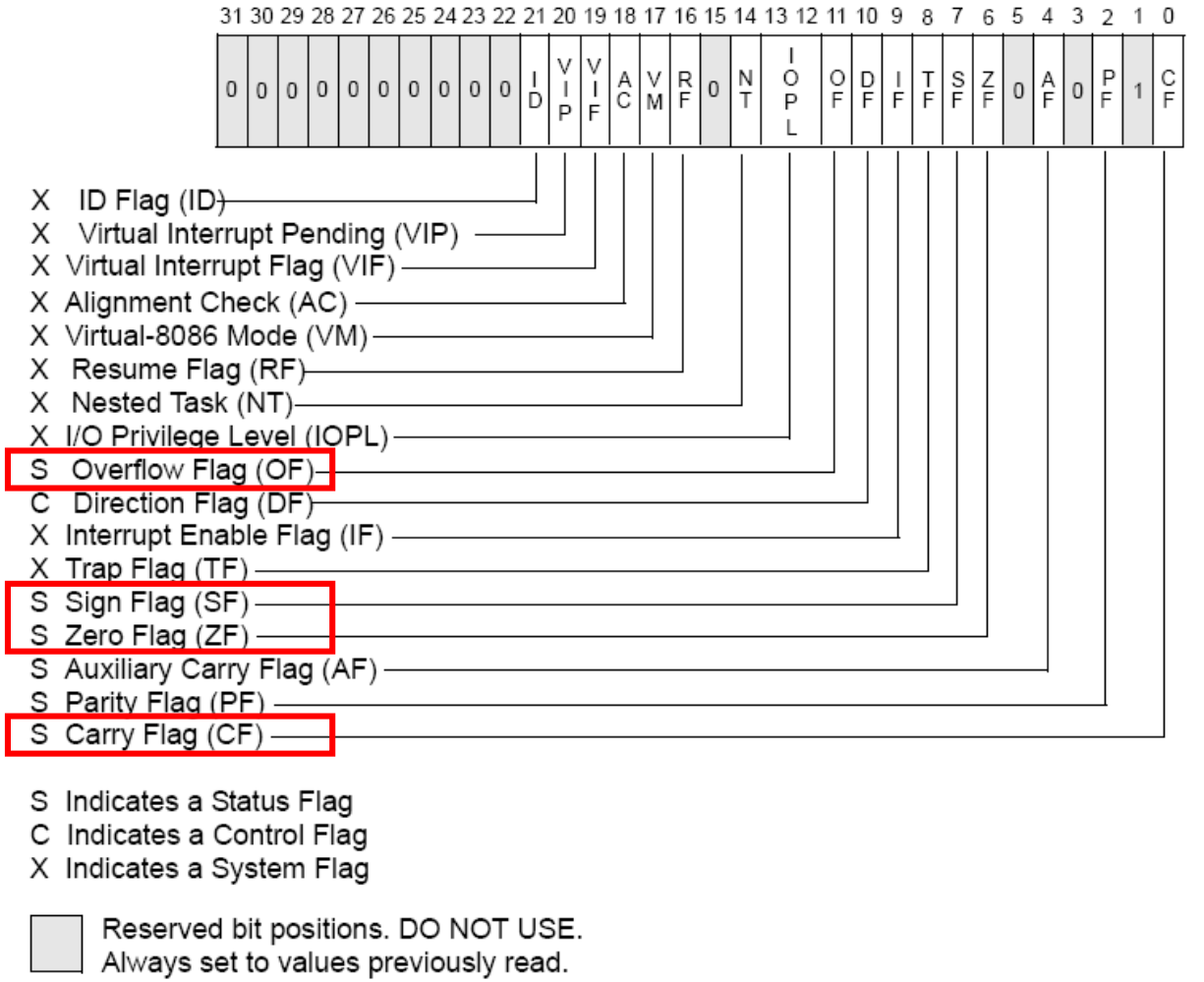
Processor State (x86-64)



Instruction Pointer

- RIP register
  - Contains the offset in the current code segment for the next instruction to be executed
    - Advanced from one instruction boundary to the next in straightline code, or
    - Moved ahead or backwards by instructions such as `JMP`, `Jcc`, `CALL`, `RET`, and `IRET`
  - Cannot be accessed directly by software
    - RIP is controlled implicitly by control transfer operations, interrupts, and exceptions
  - Because of instruction prefetching, an instruction address read from the bus does not match the value in the RIP register

EFLAGS Register



Status Flags

- CF (Carry):
  - Set if an arithmetic operation generates a carry or a borrow; indicates an overflow condition for unsigned-integer arithmetic
- ZF (Zero):
  - Set if the result is zero
- SF (Sign):
  - Set equal to the most-significant bit of the result
- OF (Overflow):
  - Set if the integer result is too large a positive number or too small a negative number to fit in the destination operand; indicates an overflow condition for signed-integer arithmetic

Condition Codes: Implicit Setting

- Implicitly set by arithmetic operations
  - Example: **`addq` *`Src`*`,` *`Dest`*** (`t = a + b`)

  - CF set if carry out from most significant bit
    - Used to detect unsigned overflow
  - ZF set if `t == 0`
  - SF set if `t < 0`
  - OF set if two's complement (signed) overflow:
    `(a > 0 && b > 0 && t < 0) || (a < 0 && b < 0 && t > 0)`

- Not set by **`leaq`**, **`incq`**, or **`decq`** instruction

Condition Codes: Compare

- Explicitly setting by Compare instruction
  - Example: `cmpq b, a`
  - Computes (a – b) without saving the result

  - CF set if carry out from most significant bit
    - Used for unsigned comparison
  - ZF set if a == b
  - SF set if (a – b) < 0 (as signed)
  - OF set if two's complement overflow:
    (a > 0 && b < 0 && (a – b) < 0) || (a < 0 && b > 0 && (a – b) > 0)

Condition Codes: Test

- Explicitly setting by Test instruction
  - Example: `testq b, a`
  - Computes (a & b) without saving the result
    - Useful to have one of the operations be a mask

  - ZF set when a & b == 0
  - SF set when a & b < 0
  - CF and OF are cleared to 0

Conditional Branch

- `jX` instructions
  - Jump to different part of code depending on condition codes

jX	Condition	Description
`jmp`	1	Unconditional
`je`	ZF	Equal / Zero
`jne`	~ZF	Not Equal / Not Zero
`js`	SF	Negative
`jns`	~SF	Nonnegative
`jg`	~(SF ^ OF) & ~ZF	Greater (Signed >)
`jge`	~(SF ^ OF)	Greater or Equal (Signed >=)
`jl`	(SF ^ OF)	Less (Signed <)
`jle`	(SF ^ OF) | ZF	Less or Equal (Signed <=)
`ja`	~CF & ~ZF	Above (Unsigned >)
`jae`	~CF	Above or Equal (Unsigned >=)
`jb`	CF	Below (Unsigned <)
`jbe`	CF | ZF	Below or Equal (Unsigned <=)

Conditional Branch Example (1)

```
long max (long x, long y)
{
    if (x > y)
        return x;
    else
        return y;
}
```

```
long goto_max (long x, long y)
{
    int ok = (x <= y);
    if (ok) goto done;
    return x;
done:
    return y;
}
```

- C allows "goto" as means of transferring control
  - Jump to position designated by label
  - Closer to machine-level programming style
- Generally considered bad coding style

Conditional Branch Example (2)

```
long goto_max (long x, long y) {
    int ok = (x <= y);
    if (ok) goto done;
    return x;
done:
    return y;
}
```

x in %rdi
y in %rsi

```
max:
    cmpq  %rsi, %rdi          # x - y?
    jle   .L3                 # if <= goto .L3
    movq  %rdi, %rax          # rax = x
    ret
.L3:
    movq  %rsi, %rax          # rax = y
    ret
```

Conditional Moves

- Conditional move instructions
  - if (Test) Dest ← Src
  - Supported in post-1995 x86 processors
  - GCC tries to use them
    - But, only when known to be safe

- Why?
  - Branches are very disruptive to instruction flow through pipelines
  - Conditional moves do not require control transfer

```
long max (long x, long y)
{
    if (x > y)
        return x;
    else
        return y;
}
```

x in %rdi
y in %rsi

```
max:
    cmpq    %rsi, %rdi
    movq    %rsi, %rax
    cmovge  %rdi, %rax
    ret
```

Bad Cases for Conditional Moves

- Expensive computations

```
val = Test(x) ? Hard1(x) : Hard2(x)
```

  - Only makes sense when computations are very simple

- Risky computations

```
val = p ? *p : 0;
```

  - May have undesirable effects

- Computations with side effects

```
val = x > 0 ? x *= 7 : x += 3;
```

  - Must be side-effect free

"Do-While" Loop (1)

- Example: compute factorial x!
  - Use backward branch to continue looping
  - Only take branch when "while" condition holds

C Code

```
long fact_do (long x)
{
    long result = 1;
    do {
      result *= x;
      x = x-1;
    } while (x > 1);
    return result;
}
```

Goto Version

```
long fact_goto (long x)
{
    long result = 1;
 loop:
    result *= x;
    x = x-1;
    if (x > 1)
      goto loop;
    return result;
}
```

"Do-While" Loop (2)

Goto Version

```
long fact_goto
     (long x) {
  long result = 1;
loop:
  result *= x;
  x = x-1;
  if (x > 1)
    goto loop;
  return result;
}
```

Registers	
%rdi	x
%rax	result

Assembly

```
fact_goto:
   movl   $1, %eax     # result = 1

.L2:
   imulq  %rdi, %rax   # result *= x
   subq   $1, %rdi     # x--
   cmpq   $1, %rdi     # compare x : 1
   jg     .L2          # if > goto Loop

   ret
```

"Do-While" Loop (3)

- General "Do-While" translation

C Code

```
do
  Body
  while (Test);
```

Goto Version

```
Loop:
  Body
  if (Test)
    goto Loop
```

- *Body* can be any C statement
  - Typically compound statement:

```
{
    Statement1;
    Statement2;
      …
    Statementn;
}
```

- *Test* is expression returning integer:
  = 0 interpreted as false, ≠ 0 interpreted as true

"While" Loop (1)

C Code

```
long fact_while (long x)
{
    long result = 1;
    while (x > 1) {
      result *= x;
      x = x-1;
    };
    return result;
}
```

First Goto Version

```
long fact_while_goto (long x)
{
    long result = 1;
loop:
    if (!(x > 1))
      goto done;
    result *= x;
    x = x-1;
    goto loop;
done:
    return result;
}
```

- Is this code equivalent to the do-while version?
- Must jump out of loop if test fails

"While" Loop (2)

C Code

```
long fact_while (long x)
{
    long result = 1;
    while (x > 1) {
      result *= x;
      x = x-1;
    };
    return result;
}
```

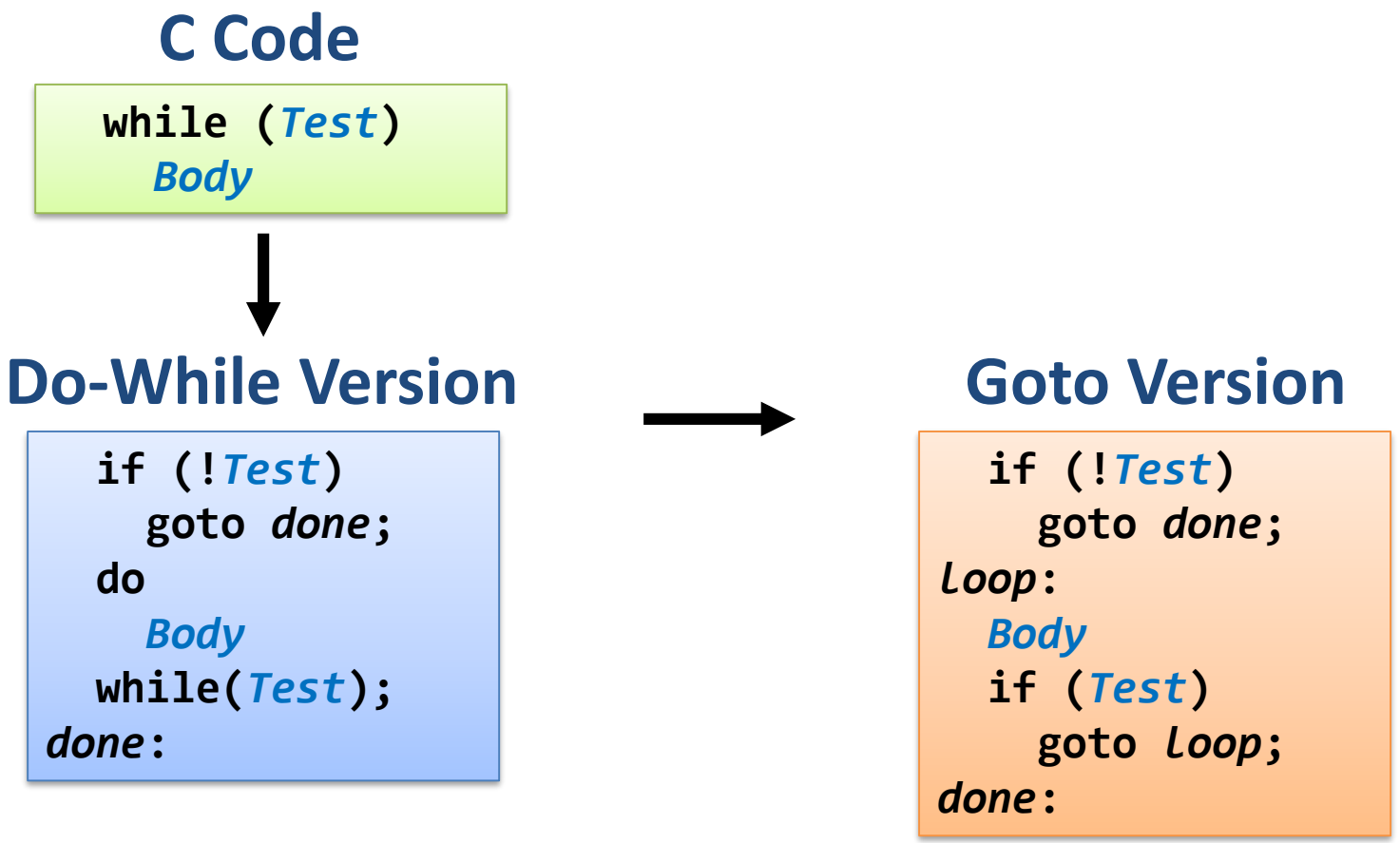
- Historically used by GCC
- Uses same inner loop as do-while version
- Guards loop entry with extra test

Second Goto Version

```
long fact_while_goto2 (long x)
{
    long result = 1;
    if (!(x > 1))
      goto done;
loop:
    result *= x;
    x = x-1;
    if (x > 1)
      goto loop;
done:
    return result;
}
```

"While" Loop (3)

- General "While" translation



"For" Loop (1)

- Example: compute x^p
  - Exploit property that $p = p_0 + 2p_1 + 4p_2 + \ldots + 2^{n-1}p_{n-1}$
  - Gives: $x^p = z_0 \cdot z_1^{\,2} \cdot (z_2^{\,2})^2 \cdot \ldots \cdot (\ldots((z_{n-1}^{\,2})^2)\ldots)^2$
    - $z_i = 1$ when $p_i = 0$
    - $z_i = x$ when $p_i = 1$
  - Complexity O(log p)

Example:
$3^{10} = 3^2 * 3^8 = 3^2 * ((3^2)^2)^2$

```
long ipwr_for(long x, unsigned long p) {
    long result;
    for (result = 1; p != 0; p = p>>1) {
      if (p & 0x1) result *= x;
      x = x*x;
    }
    return result;
}
```

"For" Loop (2)

```
long result;
for (result = 1;
     p != 0;
     p = p>>1) {
  if (p & 0x1)
    result *= x;
  x = x*x;
}
```

General Form

```
for (Init; Test; Update)
    Body
```

Init

```
result = 1
```

Test

```
p != 0
```

Update

```
p = p >> 1
```

Body

```
{
  if (p & 0x1)
    result *= x;
  x = x*x;
}
```

"For" Loop (3)

For Version

```
for (Init; Test; Update)
    Body
```

While Version

```
Init;
while (Test) {
    Body
    Update ;
}
```

Do-While Version

```
  Init;
  if (!Test)
    goto done;
  do {
    Body
    Update;
  } while (Test)
done:
```

Goto Version

```
  Init;
  if (!Test)
    goto done;
loop:
  Body
  Update;
  if (Test)
    goto loop;
done:
```

"For" Loop (4)

Goto Version

```
  Init;
  if (!Test)
    goto done;
loop:
  Body
  Update;
  if (Test)
    goto loop;
done:
```

```
  result = 1;
  if (p == 0)
    goto done;
loop:
  if (p & 0x1)
    result *= x;
  x = x*x;
  p = p >> 1;
  if (p != 0)
    goto loop;
done:
```

Init

```
result = 1
```

Test

```
p != 0
```

Update

```
p = p >> 1
```

Body

```
{
  if (p & 0x1)
    result *= x;
  x = x*x;
}
```

"Switch" Implementation

- Series of conditionals
  - Good if few cases
  - Slow if many
- Jump table (see textbook)
  - Lookup branch target and perform indirect jump
  - Avoids conditionals
  - Possible when cases are small integer constants
- Binary search tree
  - For sparse cases
  - Logarithmic performance

```
typedef enum {
   ADD, MULT, MINUS, DIV,
   MOD, BAD
}  op_type;

char unparse_symbol
(op_type op) {
  switch (op) {
  case ADD :  return '+';
  case MULT:  return '*';
  case MINUS: return '-';
  case DIV:   return '/';
  case MOD:   return '%';
  case BAD:   return '?';
  }
}
```

Summary

- C control
  - if-then-else
  - do-while, while, for
  - switch

- Assembler control
  - Conditional jump
  - Conditional move
  - Indirect jump (via jump tables)
  - Compiler generates code sequence to implement more complex control