Machine-Level Representation of Programs: Loops, Procedures

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Loop statements
  Compiling for loops to while loops
  Compiling while loops to do-while loops
  Compiling do-while loops to goto statements
  Compiling goto statements to assembly conditional jump instructions

Switch statements

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  Memory stack frames

Procedures and function calls: Transferring control
  Procedure call and return: call and ret
  Example in GDB

Procedures and function calls: Transferring data
  Data transferred via registers
  Data transferred via memory

Architecture support for recursive programming
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Class session plan

- Thursday, 3/30: Function calls in assembly. (Book chapter 3.7)
- Monday, 4/3: Arrays and data structures in assembly. (Book chapter 3.8)
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## Architecture support for recursive programming
Compiling for loops to while loops

C loop statements such as for loops, while loops, and do-while loops do not exist in assembly. They are instead constructed from conditional jump statements.

```c
unsigned long count_bits_for (unsigned long number) {
  unsigned long tally = 0;
  for (int shift=0; // init
       shift<8*sizeof(unsigned long);← // test
       shift++ // update
  ) {
    // body
    tally += 0b1 & number>>shift;
  }
  return tally;
}
```

```c
unsigned long count_bits_while (unsigned long number) {
  unsigned long tally = 0;
  int shift=0; // init
  while (shift<8*sizeof(unsigned long) ← // test
         shift++ // update
  ) {
    // body
    tally += 0b1 & number>>shift;
    shift++; // update
  }
  return tally;
}
```
Compiling while loops to do-while loops

```c
unsigned long count_bits_while (unsigned long number) {
    unsigned long tally = 0;
    int shift = 0; // init
    while (shift < 8*sizeof(unsigned long)) { // test
        // body
        tally += 0b1 & number >> shift;
        shift++; // update
    }
    return tally;
}
```

```c
unsigned long count_bits_do_while (unsigned long number) {
    unsigned long tally = 0;
    int shift = 0; // init
    do {
        // body
        tally += 0b1 & number >> shift;
        shift++; // update
    } while (shift < 8*sizeof(unsigned long)); // test
    return tally;
}
```

If initial iteration is guaranteed to run, then do one fewer test.
Compiling do-while loops to goto statements

Loops get compiled into goto statements which are readily translated to assembly.
Compiling goto statements to assembly conditional jump instructions

```c
unsigned long count_bits_goto ( unsigned long number ) {
    unsigned long tally = 0;
    int shift=0; // init

    LOOP:
        // body
        tally += 0b1 & number>>shift;
        shift++; // update

    if (shift<8*sizeof(unsigned long)) { // test
        goto LOOP;
    }
    return tally;
}
```

All C loop statements so far translate to assembly at right.

count_bits_for:
count_bits_while:
count_bits_do_while:
count_bits_goto:

```
xorl %ecx, %ecx # int shift=0; // init
xorl %eax, %eax # unsigned long tally = 0;
```

```
.LOOP:
    movq %rdi, %rdx # number
    shrq %cl, %rdx # number>>shift
    incl %ecx # shift++; // update
    andl $1, %edx. # 0b1 & number>>shift
    addq %rdx, %rax # tally += 0b1 & number>>shift
    cmpl $64, %ecx # shift<8*sizeof(unsigned long)
    jne .LOOP # goto LOOP;
    ret # return tally;
```
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Architecture support for recursive programming
Procedures and function calls

```
P(...){
  y = Q(x);
  print(y)
}
```

```
int Q(int i){
  int t = 3*i;
  int v[10];
  return v[t];
}
```

To create the abstraction of functions, need to:
- Transfer control to function and back
- Transfer data to function (parameters)
- Transfer data from function (return type)

**Figure:** Steps of a C function call. Image credit CS:APP
Structure of stack for currently executing function Q()

- P() calls Q(). P() is the caller function. Q() is the callee function.
Stack instructions: `push src` and `pop dest`

Initially

<table>
<thead>
<tr>
<th></th>
<th>%rax</th>
<th>0x123</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>%rdx</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>%rsp</td>
<td>0x108</td>
</tr>
</tbody>
</table>

pushq %rax

<table>
<thead>
<tr>
<th></th>
<th>%rax</th>
<th>0x123</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>%rdx</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>%rsp</td>
<td>0x100</td>
</tr>
</tbody>
</table>

popq %rdx

<table>
<thead>
<tr>
<th></th>
<th>%rax</th>
<th>0x123</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>%rdx</td>
<td>0x123</td>
</tr>
<tr>
<td></td>
<td>%rsp</td>
<td>0x108</td>
</tr>
</tbody>
</table>

Figure: x86-64 offers dedicated instructions to work with stack in memory. In addition to moving data, the updating of %rsp is implied. Image credit: CS:APP.
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Architecture support for recursive programming
CPU and memory state in support of procedures and functions

Assembly/Machine Code View

Relevant state in CPU:
- `%rip` register / instruction pointer / program counter
- `%rsp` register / stack pointer

Relevant state in Memory:
- Stack
Procedure call and return: `call` and `ret`
Example in GDB

```c
#include <stdio.h>

int return_neg_one() {
    return -1;
}

int main() {
    int num = return_neg_one();
    printf("%d", num);
    return 0;
}
```

Compile, and then run it in GDB:
gdb return

In GDB, see evolution of %rip, %rsp, and stack:

- (gdb) layout split
- (gdb) break return_neg_one
- (gdb) info stack
- (gdb) print /a $rip
- (gdb) print /a $rsp
- (gdb) x /a $rsp

Step past return instruction, and inspect again:

- (gdb) stepi
- (gdb) info stack
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Architecture support for recursive programming
Procedures and function calls: Transferring data

For purposes of this class, the Bomb Lab, and the CS:APP textbook, we study the x86-64 Linux Application Binary Interface (ABI). Would be different on ARM or in Windows. So, don’t memorize this, but it is helpful for PA4 Lab.

Passing parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Register / stack</th>
<th>Subset registers</th>
<th>Mnemonic(^1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st</td>
<td>%rdi</td>
<td>%edi, %di</td>
<td>Diane’s</td>
</tr>
<tr>
<td>2nd</td>
<td>%rsi</td>
<td>%esi, %si</td>
<td>silk</td>
</tr>
<tr>
<td>3rd</td>
<td>%rdx</td>
<td>%edx, %dx, %dl</td>
<td>dress</td>
</tr>
<tr>
<td>4th</td>
<td>%rcx</td>
<td>%ecx, %cx, %cl</td>
<td>cost</td>
</tr>
<tr>
<td>5th</td>
<td>%r8</td>
<td>%r8d</td>
<td>$8</td>
</tr>
<tr>
<td>6th</td>
<td>%r9</td>
<td>%r9d</td>
<td>9</td>
</tr>
<tr>
<td>7th and beyond</td>
<td>Stack</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(^1\)http://csappbook.blogspot.com/2015/08/dianes-silk-dress-costs-89.html
PA4 Defusing a Binary Bomb: `sscanf();`
Passing function return data

Function return data is passed via:

- the 64-bit %rax register
- the 32-bit subset %eax register

Example from textbook slides on assembly procedures
Slides 33 through 38.
Data transferred via memory

Structure of stack for currently executing function Q()

- P() calls Q(). P() is the caller function. Q() is the callee function.

Example from textbook slides on assembly procedures
Slides 40 through 44.
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Architecture support for recursive programming
3_recursion.c: Putting it all together to support recursion

Discussion points

- Use info stack, info args in GDB to see recursion depth
- Difference between compiling with and without -g for debugging information.
- Memory costs of recursion.
- Compilers can recognize tail recursive calls to reduce memory use. Enabled with -foptimize-sibling-calls, -O2, -O3, and -Os.