Machine-Level Programming IV: Data

15-213: Introduction to Computer Systems
8th Lecture, June 6, 2018

Instructors:
Brian Railing
Today

- **Arrays**
  - One-dimensional
  - Multi-dimensional (nested)
  - Multi-level

- **Structures**
  - Allocation
  - Access
  - Alignment

- **Floating Point**
Array Allocation

- **Basic Principle**
  
  \[ T \ A[L]; \]
  
  - Array of data type \( T \) and length \( L \)
  
  - Contiguously allocated region of \( L \times \text{sizeof}(T) \) bytes in memory

```
char string[12];
```

```
int val[5];
```

```
double a[3];
```

```
char *p[3];
```
Array Access

- **Basic Principle**
  
  $$T \ A[L] ;$$
  
  - Array of data type $$T$$ and length $$L$$
  - Identifier $$A$$ can be used as a pointer to array element 0: Type $$T^*$$

  ```c
  int val[5];
  ```

- **Reference Type Value**

<table>
<thead>
<tr>
<th>Reference</th>
<th>Type</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>val[4]</td>
<td>int</td>
<td>3</td>
</tr>
<tr>
<td>val</td>
<td>int *</td>
<td>x</td>
</tr>
<tr>
<td>val+1</td>
<td>int *</td>
<td>x + 4</td>
</tr>
<tr>
<td>&amp;val[2]</td>
<td>int *</td>
<td>x + 8</td>
</tr>
<tr>
<td>val[5]</td>
<td>int</td>
<td>??</td>
</tr>
<tr>
<td>*(val+1)</td>
<td>int</td>
<td>5             //val[1]</td>
</tr>
<tr>
<td>val + i</td>
<td>int *</td>
<td>x + 4 * i     //&amp;val[i]</td>
</tr>
</tbody>
</table>
Array Example

```c
#define ZLEN 5
typedef int zip_dig[ZLEN];

zip_dig cmu = { 1, 5, 2, 1, 3 };
zip_dig mit = { 0, 2, 1, 3, 9 };
zip_dig ucb = { 9, 4, 7, 2, 0 };```

- Declaration “zip_dig cmu” equivalent to “int cmu[5]”
- Example arrays were allocated in successive 20 byte blocks
  - Not guaranteed to happen in general
Array Accessing Example

```c
int get_digit(zip_dig z, int digit) {
    return z[digit];
}
```

x86-64

```
# %rdi = z
# %rsi = digit
movl (%rdi,%rsi,4), %eax  # z[digit]
```

- Register `%rdi` contains starting address of array
- Register `%rsi` contains array index
- Desired digit at `%rdi + 4*%rsi`
- Use memory reference `%rdi,%rsi,4`
Array Loop Example

```assembly
# %rdi = z
movl   $0, %eax
jmp    .L3
.L4:
    addl  $1, (%rdi,%rax,4)  # z[i]++
    addq  $1, %rax
.L3:
    cmpq  $4, %rax  # i:4
    jbe    .L4  # if <=, goto loop
rep; ret
```
Array Loop Example

```c
void zincr(zip_dig z) {
    size_t i;
    for (i = 0; i < ZLEN; i++)
        z[i]++;
}
```

```
# %rdi = z
    movl    $0, %eax          #   i = 0
    jmp     .L3               #   goto middle
.L4:
    addl    $1, (%rdi,%rax,4) #   z[i]++
    addq    $1, %rax          #   i++
.L3:
    cmpq    $4, %rax          #   i:4
    jbe     .L4               #   if <=, goto loop
    rep; ret
```
Understanding Pointers & Arrays #1

<table>
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<th>An</th>
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</tr>
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<tbody>
<tr>
<td></td>
<td>Cmp</td>
<td>Bad</td>
</tr>
<tr>
<td>int A1[3]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>int *A2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **Cmp**: Compiles (Y/N)
- **Bad**: Possible bad pointer reference (Y/N)
- **Size**: Value returned by `sizeof`
Understanding Pointers & Arrays #1

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</thead>
<tbody>
<tr>
<td></td>
<td>Cmp</td>
<td>Bad</td>
</tr>
<tr>
<td>int *A2</td>
<td>Y</td>
<td>N</td>
</tr>
</tbody>
</table>

- **Cmp**: Compiles (Y/N)
- **Bad**: Possible bad pointer reference (Y/N)
- **Size**: Value returned by `sizeof`
# Understanding Pointers & Arrays #2

<table>
<thead>
<tr>
<th>Decl</th>
<th>An</th>
<th>*An</th>
<th>**An</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cmp</td>
<td>Bad</td>
<td>Size</td>
</tr>
<tr>
<td>int  A1[3]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>int  *A2[3]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>int  (*A3)[3]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>int  (*A4[3])</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **Cmp**: Compiles (Y/N)
- **Bad**: Possible bad pointer reference (Y/N)
- **Size**: Value returned by `sizeof`
## Understanding Pointers & Arrays #2

<table>
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<tr>
<th>Decl</th>
<th>An</th>
<th>*An</th>
<th>**An</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cmp</td>
<td>Bad</td>
<td>Size</td>
</tr>
<tr>
<td>int A1[3]</td>
<td>Y</td>
<td>N</td>
<td>12</td>
</tr>
<tr>
<td>int *A2[3]</td>
<td>Y</td>
<td>N</td>
<td>24</td>
</tr>
<tr>
<td>int (*A3)[3]</td>
<td>Y</td>
<td>N</td>
<td>8</td>
</tr>
<tr>
<td>int (*A4[3])</td>
<td>Y</td>
<td>N</td>
<td>24</td>
</tr>
</tbody>
</table>

### Diagram:
- **A1**
- **A2/A4**
- **A3**

Allocated int
Unallocated int
Allocated pointer
Unallocated pointer
Multidimensional (Nested) Arrays

- **Declaration**
  - \( T \ A[R][C]; \)
  - 2D array of data type \( T \)
  - \( R \) rows, \( C \) columns
  - Type \( T \) element requires \( K \) bytes

- **Array Size**
  - \( R \times C \times K \) bytes

- **Arrangement**
  - Row-Major Ordering

\[
\begin{array}{cccc}
A[0][0] & \cdots & \cdots & A[0][C-1] \\
\vdots & \ddots & \ddots & \vdots \\
A[R-1][0] & \cdots & \cdots & A[R-1][C-1] \\
\end{array}
\]

**Diagram:**
- \( A[R][C]; \)
- \( 4 \times R \times C \) bytes
Nested Array Example

```c
#define PCOUNT 4
zip_dig pgh[PCOUNT] =
    {{1, 5, 2, 0, 6},
    {1, 5, 2, 1, 3 },
    {1, 5, 2, 1, 7 },
    {1, 5, 2, 2, 1 }};
```

- **“zip_dig pgh[4]” equivalent to “int pgh[4][5]”**
  - Variable `pgh`: array of 4 elements, allocated contiguously
  - Each element is an array of 5 int’s, allocated contiguously

- **“Row-Major” ordering of all elements in memory**
Nested Array Row Access

**Row Vectors**

- \( A[i] \) is array of \( C \) elements
- Each element of type \( T \) requires \( K \) bytes
- Starting address \( A + i \times (C \times K) \)

```c
int A[R][C];
```

![Diagram of nested array row access](diagram.png)
**Nested Array Row Access Code**

```c
int *get_pgh_zip(int index) {
    return pgh[index];
}

int pgh[5]
```

**Row Vector**
- `pgh[index]` is array of 5 int’s
- Starting address `pgh + 20 * index`

**Machine Code**
- Computes and returns address
- Compute as `pgh + 4 * (index + 4 * index)`
Nested Array Element Access

- **Array Elements**
  - $A[i][j]$ is element of type $T$, which requires $K$ bytes
  - Address $A + i \times (C \times K) + j \times K$
    $$= A + (i \times C + j) \times K$$

```c
int A[R][C];
```

```plaintext
A + (i*C*4) + (j*4)
```
Nested Array Element Access Code

Array Elements

- \( pgh[\text{index}][\text{dig}] \) is int
- Address: \( pgh + 20*\text{index} + 4*\text{dig} \)
  
  \[ pgh + 4*(5*\text{index} + \text{dig}) \]

```
int get_pgh_digit(int index, int dig)
{
  return pgh[index][dig];
}
```

```
leaq (%rdi,%rdi,4), %rax # 5*index
addl %rax, %rsi # 5*index+dig
movl pgh(,%rsi,4), %eax # M[pgh + 4*(5*index+dig)]
```
Multi-Level Array Example

■ Variable `univ` denotes array of 3 elements
■ Each element is a pointer
  ▪ 8 bytes
■ Each pointer points to array of int’s

```c
zip_dig cmu = { 1, 5, 2, 1, 3 };
zip_dig mit = { 0, 2, 1, 3, 9 };
zip_dig ucb = { 9, 4, 7, 2, 0 };

#define UCOUNT 3
int *univ[UCOUNT] = {mit, cmu, ucb};
```
Element Access in Multi-Level Array

```c
int get_univ_digit
    (size_t index, size_t digit)
{
    return univ[index][digit];
}
```

### Computation

- **Element access** `Mem[Mem[univ+8*index]+4*digit]`
- **Must do two memory reads**
  - First get pointer to row array
  - Then access element within array
Array Element Accesses

Nested array

```
int get_pgh_digit(size_t index, size_t digit) {
    return pgh[index][digit];
}
```

Multi-level array

```
int get_univ_digit(size_t index, size_t digit) {
    return univ[index][digit];
}
```

Accesses looks similar in C, but address computations very different:

```
Mem[pgh+20*index+4*digit]  Mem[Mem[univ+8*index]+4*digit]
```
\( N \times N \) **Matrix Code**

- **Fixed dimensions**
  - Know value of \( N \) at compile time

- **Variable dimensions, explicit indexing**
  - Traditional way to implement dynamic arrays

- **Variable dimensions, implicit indexing**
  - Now supported by gcc

```c
#define N 16
typedef int fix_matrix[N][N];
/* Get element \( A[i][j] \) */
int fix_ele(fix_matrix A,
            size_t i, size_t j)
{
    return A[i][j];
}

#define IDX(n, i, j) ((i)*(n)+(j))
/* Get element \( A[i][j] \) */
int vec_ele(size_t n, int *A,
            size_t i, size_t j)
{
    return A[IDX(n,i,j)];
}

/* Get element \( a[i][j] \) */
int var_ele(size_t n, int A[n][n],
            size_t i, size_t j) {
    return A[i][j];
}
```
16 X 16 Matrix Access

Array Elements

- int A[16][16];
- Address A + i * (C * K) + j * K
- C = 16, K = 4

```c
/* Get element A[i][j] */
int fix_ele(fix_matrix A, size_t i, size_t j) {
    return A[i][j];
}
```

```assembly
# A in %rdi, i in %rsi, j in %rdx
salq $6, %rsi          # 64*i
addq %rsi, %rdi         # A + 64*i
movl (%rdi,%rdx,4), %eax  # M[A + 64*i + 4*j]
ret
```
### $n \times n$ Matrix Access

**Array Elements**

- `size_t n;`
- `int A[n][n];`
- Address $A + i \times (C \times K) + j \times K$
- $C = n, K = 4$
- Must perform integer multiplication

```c
/* Get element $A[i][j]$ */
int var_ele(size_t n, int A[n][n], size_t i, size_t j)
{
    return A[i][j];
}
```

```
/* n in %rdi, A in %rsi, i in %rdx, j in %rcx */
imulq %rdx, %rdi           # n*i
leaq (%rsi,%rdi,4), %rax  # A + 4*n*i
movl (%rax,%rcx,4), %eax # A + 4*n*i + 4*j
ret
```
Example: Array Access

```c
#include <stdio.h>
define ZLEN 5
define PCOUNT 4
typedef int zip_dig[ZLEN];

int main(int argc, char** argv) {
    zip_dig pgh[PCOUNT] =
    {{1, 5, 2, 0, 6},
     {1, 5, 2, 1, 3 },
     {1, 5, 2, 1, 7 },
     {1, 5, 2, 2, 1 }};
    int *linear_zip = (int *) pgh;
    int *zip2 = (int *) pgh[2];
    int result =
     pgh[0][0] +
     linear_zip[7] +
     *(linear_zip + 8) +
     zip2[1];
    printf("result: %d\n", result);
    return 0;
}
```

```
linux> ./array
result: 9
```
Example: Array Access

#include <stdio.h>
#define ZLEN 5
#define PCOUNT 4
typedef int zip_dig[ZLEN];

int main(int argc, char** argv) {
    zip_dig pgh[PCOUNT] =
        {{1, 5, 2, 0, 6},
         {1, 5, 2, 1, 3 },
         {1, 5, 2, 1, 7 },
         {1, 5, 2, 2, 1 }};
    int *linear_zip = (int *) pgh;
    int *zip2 = (int *) pgh[2];
    int result =
        pgh[0][0] +
        linear_zip[7] +
        *(linear_zip + 8) +
        zip2[1];
    printf("result: %d\n", result);
    return 0;
}

linux> ./array
result: 9
### Understanding Pointers & Arrays #3

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<tr>
<td></td>
<td>Cmp</td>
<td>Bad</td>
<td>Size</td>
</tr>
<tr>
<td>int  A1[3][5]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>int  *A2[3][5]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>int  (**A3)[3][5]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>int  *(A4[3][5])</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>int  (**A5[3])[5]</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **Cmp**: Compiles (Y/N)
- **Bad**: Possible bad pointer reference (Y/N)
- **Size**: Value returned by `sizeof`
Allocated pointer

Allocated pointer to unallocated int

Unallocated pointer

Allocated int

Unallocated int

A1

A2/A4

A3

A5

Declaration

int A1[3][5]
int *A2[3][5]
int (*A3)[3][5]
int *(A4[3][5])
int (*A5[3])[5]
# Understanding Pointers & Arrays #3

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<tbody>
<tr>
<td></td>
<td>Cmp</td>
<td>Bad</td>
<td>Size</td>
</tr>
<tr>
<td>int A1[3][5]</td>
<td>Y</td>
<td>N</td>
<td>60</td>
</tr>
<tr>
<td>int *A2[3][5]</td>
<td>Y</td>
<td>N</td>
<td>120</td>
</tr>
<tr>
<td>int (*A3)[3][5]</td>
<td>Y</td>
<td>N</td>
<td>8</td>
</tr>
<tr>
<td>int *(A4[3][5])</td>
<td>Y</td>
<td>N</td>
<td>120</td>
</tr>
<tr>
<td>int (**A5[3])[5]</td>
<td>Y</td>
<td>N</td>
<td>24</td>
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</tbody>
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- **Cmp**: Compiles (Y/N)
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<tr>
<td>int (*A3)[3][5]</td>
<td>Y</td>
</tr>
<tr>
<td>int *(A4[3][5])</td>
<td>Y</td>
</tr>
<tr>
<td>int (**A5[3])[5]</td>
<td>Y</td>
</tr>
</tbody>
</table>
Today

- **Arrays**
  - One-dimensional
  - Multi-dimensional (nested)
  - Multi-level

- **Structures**
  - Allocation
  - Access
  - Alignment

- **Floating Point**
Structure Representation

- Structure represented as block of memory
  - Big enough to hold all of the fields
- Fields ordered according to declaration
  - Even if another ordering could yield a more compact representation
- Compiler determines overall size + positions of fields
  - Machine-level program has no understanding of the structures in the source code

```c
struct rec {
    int a[4];
    size_t i;
    struct rec *next;
};
```
Generating Pointer to Structure Member

```c
struct rec {
    int a[4];
    size_t i;
    struct rec *next;
};
```

**Generating Pointer to Array Element**

- Offset of each structure member determined at compile time
- Compute as \( r + 4 \times \text{idx} \)

```c
int *get_ap
    (struct rec *r, size_t idx)
{
    return &r->a[idx];
}
```

```
# r in %rdi, idx in %rsi
leaq (%rdi,%rsi,4), %rax
ret
```
Following Linked List

- C Code

```c
void set_val
    (struct rec *r, int val)
{
    while (r) {
        int i = r->i;
        r->a[i] = val;
        r = r->next;
    }
}
```

```
.L11:                         # loop:
    movslq  16(%rdi), %rax      #   i = M[r+16]
    movl    %esi, (%rdi,%rax,4) #   M[r+4*i] = val
    movq    24(%rdi), %rdi      #   r = M[r+24]
    testq   %rdi, %rdi          #   Test r
    jne     .L11                #   if !=0 goto loop
```

```
struct rec {
    int a[4];
    int i;
    struct rec *next;
};
```

```c
void set_val
    (struct rec *r, int val)
{
    while (r) {
        int i = r->i;
        r->a[i] = val;
        r = r->next;
    }
}
```
**Structures & Alignment**

- **Unaligned Data**
  - Primitive data type requires $K$ bytes
  - Address must be multiple of $K$

- **Aligned Data**
  - Primitive data type requires $K$ bytes
  - Address must be multiple of $K$

```c
struct S1 {
    char c;
    int i[2];
    double v;
} *p;
```
Alignment Principles

- **Aligned Data**
  - Primitive data type requires $K$ bytes
  - Address must be multiple of $K$
  - Required on some machines; advised on x86-64

- **Motivation for Aligning Data**
  - Memory accessed by (aligned) chunks of 4 or 8 bytes (system dependent)
    - Inefficient to load or store datum that spans quad word boundaries
    - Virtual memory trickier when datum spans 2 pages

- **Compiler**
  - Inserts gaps in structure to ensure correct alignment of fields
Specific Cases of Alignment (x86-64)

- **1 byte: char, ...**
  - no restrictions on address

- **2 bytes: short, ...**
  - lowest 1 bit of address must be 0₂

- **4 bytes: int, float, ...**
  - lowest 2 bits of address must be 00₂

- **8 bytes: double, long, char *, ...**
  - lowest 3 bits of address must be 000₂
Satisfying Alignment with Structures

- **Within structure:**
  - Must satisfy each element’s alignment requirement

- **Overall structure placement**
  - Each structure has alignment requirement $K$
    - $K =$ Largest alignment of any element
  - Initial address & structure length must be multiples of $K$

- **Example:**
  - $K = 8$, due to `double` element

```c
struct S1 {
    char c;
    int i[2];
    double v;
} *p;
```
Meeting Overall Alignment Requirement

- For largest alignment requirement $K$
- Overall structure must be multiple of $K$

```c
struct S2 {
    double v;
    int i[2];
    char c;
} *p;
```

![Diagram showing alignment requirements](image)
Arrays of Structures

- Overall structure length multiple of K
- Satisfy alignment requirement for every element

```
struct S2 {
    double v;
    int i[2];
    char c;
} a[10];
```
Accessing Array Elements

- Compute array offset 12*idx
  - `sizeof(S3)`, including alignment spacers

- Element `j` is at offset 8 within structure

- Assembler gives offset `a+8`
  - Resolved during linking

```c
struct S3 {
    short i;
    float v;
    short j;
} a[10];
```

```c
short get_j(int idx) {
    return a[idx].j;
}
```

```
# %rdi = idx
leaq (%rdi,%rdi,2),%rax # 3*idx
movzwl a+8(,%rax,4),%eax
```
Saving Space

- Put large data types first

```
struct S4 {
    char c;
    int i;
    char d;
} *p;
```

```
struct S5 {
    int i;
    char c;
    char d;
} *p;
```

- Effect (K=4)

<table>
<thead>
<tr>
<th>c</th>
<th>3 bytes</th>
<th>i</th>
<th>d</th>
<th>3 bytes</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>i</th>
<th>2 bytes</th>
<th>c</th>
<th>d</th>
</tr>
</thead>
</table>
Example Struct Exam Question

Problem 5. (8 points):

*Struct alignment.* Consider the following C struct declaration:

```c
typedef struct {
    char a;
    long b;
    float c;
    char d[3];
    int *e;
    short *f;
} foo;
```

1. Show how `foo` would be allocated in memory on an x86-64 Linux system. Label the bytes with the names of the various fields and clearly mark the end of the struct. Use an X to denote space that is allocated in the struct as padding.

**Example Struct Exam Question**

**Problem 5. (8 points):**
*Struct alignment.* Consider the following C struct declaration:

```c
typedef struct {
    char a;
    long b;
    float c;
    char d[3];
    int *e;
    short *f;
} foo;
```

1. Show how `foo` would be allocated in memory on an x86-64 Linux system. Label the bytes with the names of the various fields and clearly mark the end of the struct. Use an X to denote space that is allocated in the struct as padding.

![Diagram of memory allocation]

---

Example Struct Exam Question (Cont’d)

Problem 5. (8 points):

Struct alignment. Consider the following C struct declaration:

typedef struct {
    char a;
    long b;
    float c;
    char d[3];
    int *e;
    short *f;
} foo;

2. Rearrange the elements of foo to conserve the most space in memory. Label the bytes with the names of the various fields and clearly mark the end of the struct. Use an X to denote space that is allocated in the struct as padding.

Example Struct Exam Question (Cont’d)

Problem 5. (8 points):
Struct alignment. Consider the following C struct declaration:

typedef struct {
    char a;
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names of the various fields and clearly mark the end of the struct. Use an X to denote space that is
allocated in the struct as padding.

Today

- Arrays
  - One-dimensional
  - Multi-dimensional (nested)
  - Multi-level

- Structures
  - Allocation
  - Access
  - Alignment

- Floating Point
Background

- History
  - x87 FP
    - Legacy, very ugly
  - SSE FP
    - Supported by Shark machines
    - Special case use of vector instructions
  - AVX FP
    - Newest version
    - Similar to SSE
    - Documented in book
Programming with SSE3

XMM Registers

- 16 total, each 16 bytes
- 16 single-byte integers
- 8 16-bit integers
- 4 32-bit integers
- 4 single-precision floats
- 2 double-precision floats
- 1 single-precision float
- 1 double-precision float
Scalar & SIMD Operations

- Scalar Operations: Single Precision
  - addss
  
- SIMD Operations: Single Precision
  - addps
  
- Scalar Operations: Double Precision
  - addsd
FP Basics

- Arguments passed in %xmm0, %xmm1, ...
- Result returned in %xmm0
- All XMM registers caller-saved

```c
float fadd(float x, float y)
{
    return x + y;
}

double dadd(double x, double y)
{
    return x + y;
}
```

```assembly
# x in %xmm0, y in %xmm1
addss %xmm1, %xmm0
ret
```

```assembly
# x in %xmm0, y in %xmm1
addsd %xmm1, %xmm0
ret
```
FP Memory Referencing

- Integer (and pointer) arguments passed in regular registers
- FP values passed in XMM registers
- Different mov instructions to move between XMM registers, and between memory and XMM registers

```c
double dincr(double *p, double v)
{
    double x = *p;
    *p = x + v;
    return x;
}
```

```
# p in %rdi, v in %xmm0
movapd  %xmm0, %xmm1  # Copy v
movsd   (%rdi), %xmm0  # x = *p
addsd   %xmm0, %xmm1  # t = x + v
movsd   %xmm1, (%rdi)  # *p = t
ret
```
Other Aspects of FP Code

- **Lots of instructions**
  - Different operations, different formats, ...

- **Floating-point comparisons**
  - Instructions `ucomiss` and `ucomisd`
  - Set condition codes CF, ZF, and PF

- **Using constant values**
  - Set XMM0 register to 0 with instruction `xorpd %xmm0, %xmm0`
  - Others loaded from memory
Summary

- **Arrays**
  - Elements packed into contiguous region of memory
  - Use index arithmetic to locate individual elements

- **Structures**
  - Elements packed into single region of memory
  - Access using offsets determined by compiler
  - Possible require internal and external padding to ensure alignment

- **Combinations**
  - Can nest structure and array code arbitrarily

- **Floating Point**
  - Data held and operated on in XMM registers