

Formal Methods for C

Seminar – Summer Semester 2014

Daniel Dietsch, Sergio Feo Arenis, Marius Greitschus, **Bernd Westphal**

– 2014-04 – main –

Content

- Brief history
- Comments
- Declarations and Scopes
 - Variables
 - Expressions and Statements
 - Functions
 - Scopes
- Pointers
- Dynamic Storage & Storage Duration
- Storage Class Specifiers
- Strings and I/O
- Tools & Modules
- Formal Methods for C
- Common Errors


– 2014-04 – overview –

Function Pointers

Functions in the System's Memory

```
1 void f() { return; }
```

the compiler chose to store the machine code of 'f' at memory cell with address 0x1001



| | | | | | | | | |
|--------|---------------|--------|--------|--------|--------|--------|--------|--------|
| 0x1000 | 0x1001 RET | 0x1002 | ... | 0x1003 | 0x1004 | 0x1005 | 0x1006 | 0x1007 |
| 0x1008 | 0x1009 | 0x100A | 0x100B | 0x100C | 0x100D | 0x100E | 0x100F | |
| 0x1010 | 0x1011 | 0x1012 | 0x1013 | 0x1014 | 0x1015 | 0x1016 | 0x1017 | |
| | | | | ... | | | | |

Calling Functions

```
1 void f() { return; }  
2 f();
```

Calling Functions

```
1 void f() { return; }  
2 f();
```

calling 'f' means
machine op CALL with
address of callee (here:
f, address 0x1001)

| | | | | | | | |
|--------|---------------|--------|----------------|----------------|----------------|--------|--------|
| 0x1000 | 0x1001 RET | 0x1002 | 0x1003 | 0x1004 | 0x1005 | 0x1006 | 0x1007 |
| 0x1008 | 0x1009 | 0x100A | 0x100B CALL | 0x100C 0x10 | 0x100D 0x01 | 0x100E | 0x100F |
| 0x1010 | 0x1011 | 0x1012 | 0x1013 | 0x1014 | 0x1015 | 0x1016 | 0x1017 |
| | | | | ... | | | |

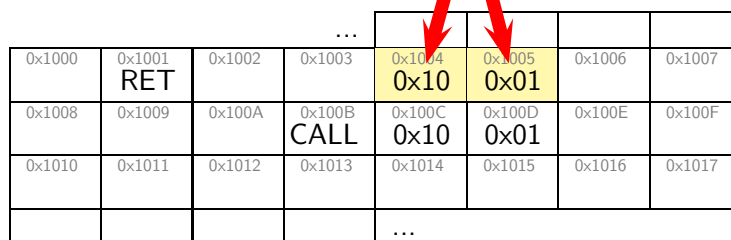
A Pointer to 'f' (16-bit Architecture)

```
1 void f() { return; }
2 f();
3 void (*p) () = &f;
```

A Pointer to 'f' (16-bit Architecture)

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1 void f() { return; }
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'p' is a variable which stores the address of a function (here: of 'f')



| | | | | | | | |
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Dereference Function Pointers

```
1 void f() { return; }
2 f();
3 void (*p) () = &f;
4 (*p)();
```

2014-04 - pointers -

| | | | | | | | |
|--------|--------|--------|--------|--------|--------|--------|--------|
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| 0x1010 | 0x1011 | 0x1012 | 0x1013 | 0x1014 | 0x1015 | 0x1016 | 0x1017 |
| MOV | 0x10 | 0x04 | R | CALL | R | | |
| | | | | ... | | | |

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Dereference Function Pointers

```
1 void f() { return; }
2 f();
3 void (*p) () = &f;
4 (*p)();
```

calling via **'p'** means read
value of **p** (here: 0x1001)
into register **R**...

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| | | | | | | | |
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Dereference Function Pointers

```

1 void f() { return; }
2 f();
3 void (*p) () = &f;
4 (*p)();

```

calling via '**p**' means read
value of **p** (here: 0x1001)
into register *R*...

...and then machine op
CALL with *R*, calls
address stored in *R*

| | | | | | | | |
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| MOV | 0x10 | 0x04 | <i>R</i> | CALL | <i>R</i> | | |
| | | | | ... | | | |

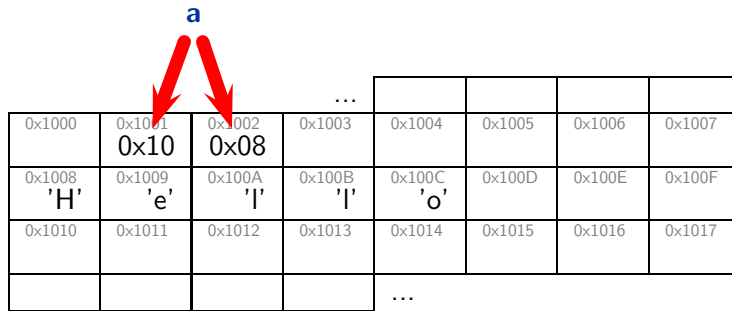
Pointers vs. Arrays

Arrays

reserve some space
for 5 chars...

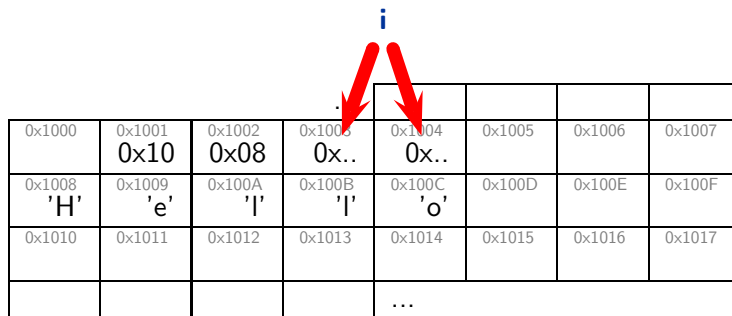
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1 char a[5] = { 'H', 'e', 'l', 'l', 'o' };
```

...and let **a** point
to that space



Arrays

```
1 char a[5] = { 'H', 'e', 'l', 'l', 'o' };  
2 int i;  
3 for (i = 0; i < 5; ++i)  
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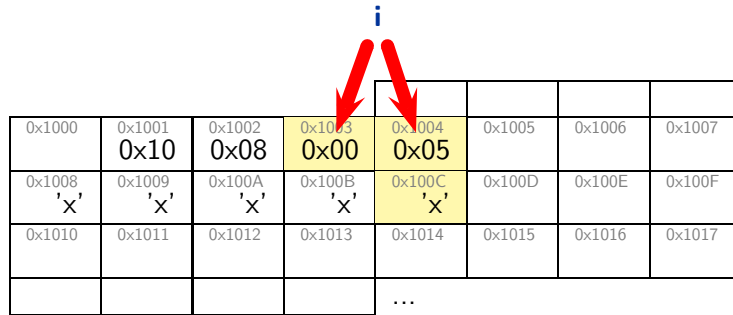
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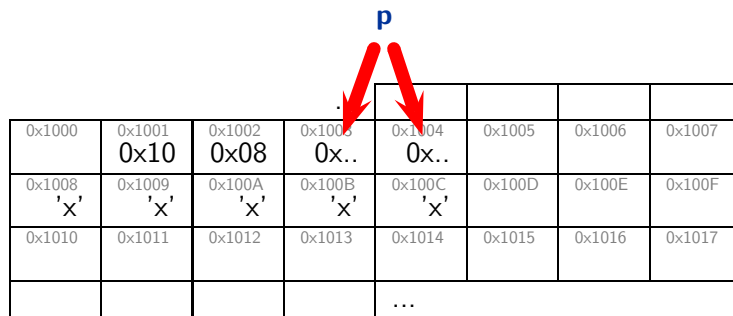


Arrays vs. Pointers

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| | 0x10 | 0x08 | 0x10 | 0x0B | | | |
| 0x1008 | 0x1009 | 0x100A | 0x100B | 0x100C | 0x100D | 0x100E | 0x100F |
| 'o' | 'o' | 'o' | 'x' | 'x' | | | |
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| 0x1000 | 0x1001 | 0x1002 | 0x1003 | 0x1004 | 0x1005 | 0x1006 | 0x1007 |
| | 0x10 | 0x08 | 0x10 | 0x0C | | | |
| 0x1008 | 0x1009 | 0x100A | 0x100B | 0x100C | 0x100D | 0x100E | 0x100F |
| 'o' | 'o' | 'o' | 'o' | 'x' | | | |
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| | | | | ... | | | |

Integer Arrays

reserve some space
for 3 ints...

```
1 int a[3] = { 10, 010, 0x1234 };
```

...and let **a** point
to that space

a

| | | | | | | | |
|--------|----------------|----------------|----------------|----------------|----------------|--------|--------|
| 0x1000 | 0x1001 0x10 | 0x1002 0x08 | ... | 0x1004 | 0x1005 | 0x1006 | 0x1007 |
| 0x1008 | 0x1009 0x0A | 0x100A 0x00 | 0x100B 0x08 | 0x100C 0x12 | 0x100D 0x34 | 0x100E | 0x100F |
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| | | | | ... | | | |

Integer Arrays

```
1 int a[3] = { 10, 010, 0x1234 };
2 int i;
3 for (i = 0; i < 3; ++i)
4     a[i] = 0x27;
```

i

| | | | | | | | |
|--------|----------------|----------------|----------------|----------------|----------------|--------|--------|
| 0x1000 | 0x1001 0x10 | 0x1002 0x08 | 0x1003 0x.. | 0x1004 0x.. | 0x1005 | 0x1006 | 0x1007 |
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| | 0x10 | 0x08 | 0x00 | 0x01 | | | |
| 0x1008 | 0x1009 | 0x100A | 0x100B | 0x100C | 0x100D | 0x100E | 0x100F |
| 0x00 | 0x27 | 0x00 | 0x08 | 0x12 | 0x34 | | |
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| 0x00 | 0x27 | 0x00 | 0x27 | 0x00 | 0x27 | | |
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| | | | | ... | | | |

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Integer Arrays vs. Pointers

```

1  int a[3] = { 10, 010, 0x1234 };
2  int* p = a;
3  for (int i = 0; i < 3; ++i)
4    *p = 0x3421;

```

p

| | | | | | | | |
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| | 0x10 | 0x08 | 0x.. | 0x.. | | | |
| 0x1008 | 0x1009 | 0x100A | 0x100B | 0x100C | 0x100D | 0x100E | 0x100F |
| 0x00 | 0x27 | 0x00 | 0x27 | 0x00 | 0x27 | | |
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| 0x00 | 0x27 | 0x00 | 0x27 | 0x00 | 0x27 | | |
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2 int* p = a;
3 for (int i = 0; i < 3; ++p)
4     *p = 0x3421;
```

p

| | | | | | | | |
|--------|--------|--------|--------|--------|--------|--------|--------|
| 0x1000 | 0x1001 | 0x1002 | 0x1003 | 0x1004 | 0x1005 | 0x1006 | 0x1007 |
| | 0x10 | 0x08 | 0x10 | 0x0E | | | |
| 0x1008 | 0x1009 | 0x100A | 0x100B | 0x100C | 0x100D | 0x100E | 0x100F |
| | 0x34 | 0x21 | 0x34 | 0x34 | 0x21 | | |
| 0x1010 | 0x1011 | 0x1012 | 0x1013 | 0x1014 | 0x1015 | 0x1016 | 0x1017 |
| | | | | ... | | | |

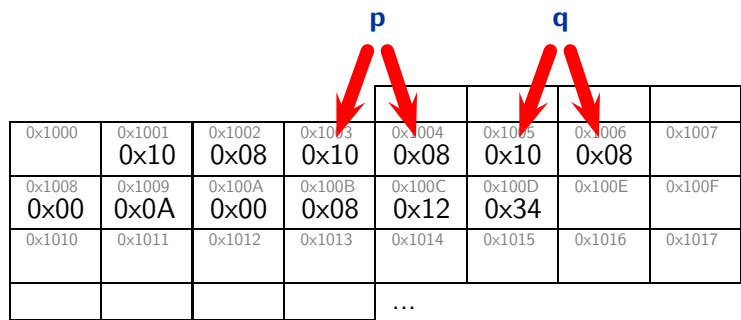
— 2014-04 — pointers —

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Pointers to 'void', Pointer Arithmetic

Pointer to 'void'

```
1 int[3] a = { 10, 010, 0x1234 };
2 int* p = a;
3 void* q = a;
4 for (int i = 0; i < 3; ++i) {
5     p++;
6     q++;
7 }
```



Pointer to 'void'

```
1 int[3] a = { 10, 010, 0x1234 };
2 int* p = a;
3 void* q = a;
4 for (int i = 0; i < 3; ++i) {
5     p++;
6     q++;
7 }
```

| | | | | | | | |
|--------|--------|--------|--------|--------|--------|--------|--------|
| 0x1000 | 0x1001 | 0x1002 | 0x1003 | 0x1004 | 0x1005 | 0x1006 | 0x1007 |
| | 0x10 | 0x08 | 0x10 | 0x0A | 0x10 | 0x08 | |
| 0x1008 | 0x1009 | 0x100A | 0x100B | 0x100C | 0x100D | 0x100E | 0x100F |
| 0x00 | 0x0A | 0x00 | 0x08 | 0x12 | 0x34 | | |
| 0x1010 | 0x1011 | 0x1012 | 0x1013 | 0x1014 | 0x1015 | 0x1016 | 0x1017 |
| | | | | ... | | | |

Pointer to 'void'

```
1 int[3] a = { 10, 010, 0x1234 };
2 int* p = a;
3 void* q = a;
4 for (int i = 0; i < 3; ++i) {
5     p++;
6     q++;
7 }
```

| | | | | | | | |
|--------|--------|--------|--------|--------|--------|--------|--------|
| 0x1000 | 0x1001 | 0x1002 | 0x1003 | 0x1004 | 0x1005 | 0x1006 | 0x1007 |
| | 0x10 | 0x08 | 0x10 | 0x0A | 0x10 | 0x09 | |
| 0x1008 | 0x1009 | 0x100A | 0x100B | 0x100C | 0x100D | 0x100E | 0x100F |
| 0x00 | 0x0A | 0x00 | 0x08 | 0x12 | 0x34 | | |
| 0x1010 | 0x1011 | 0x1012 | 0x1013 | 0x1014 | 0x1015 | 0x1016 | 0x1017 |
| | | | | ... | | | |

Pointer to 'void'

```
1 int[3] a = { 10, 010, 0x1234 };
2 int* p = a;
3 void* q = a;
4 for (int i = 0; i < 3; ++i) {
5     p++;
6     q++;
7 }
```

| | | | | | | | |
|--------|--------|--------|--------|--------|--------|--------|--------|
| 0x1000 | 0x1001 | 0x1002 | 0x1003 | 0x1004 | 0x1005 | 0x1006 | 0x1007 |
| | 0x10 | 0x08 | 0x10 | 0x0C | 0x10 | 0x09 | |
| 0x1008 | 0x1009 | 0x100A | 0x100B | 0x100C | 0x100D | 0x100E | 0x100F |
| 0x00 | 0x0A | 0x00 | 0x08 | 0x12 | 0x34 | | |
| 0x1010 | 0x1011 | 0x1012 | 0x1013 | 0x1014 | 0x1015 | 0x1016 | 0x1017 |
| | | | | ... | | | |

Pointer to 'void'

```
1 int[3] a = { 10, 010, 0x1234 };
2 int* p = a;
3 void* q = a;
4 for (int i = 0; i < 3; ++i) {
5     p++;
6     q++;
7 }
```

| | | | | | | | |
|--------|--------|--------|--------|--------|--------|--------|--------|
| 0x1000 | 0x1001 | 0x1002 | 0x1003 | 0x1004 | 0x1005 | 0x1006 | 0x1007 |
| | 0x10 | 0x08 | 0x10 | 0x0C | 0x10 | 0x0A | |
| 0x1008 | 0x1009 | 0x100A | 0x100B | 0x100C | 0x100D | 0x100E | 0x100F |
| 0x00 | 0x0A | 0x00 | 0x08 | 0x12 | 0x34 | | |
| 0x1010 | 0x1011 | 0x1012 | 0x1013 | 0x1014 | 0x1015 | 0x1016 | 0x1017 |
| | | | | ... | | | |

Pointer to 'void'

```
1 int[3] a = { 10, 010, 0x1234 };
2 int* p = a;
3 void* q = a;
4 for (int i = 0; i < 3; ++i) {
5     p++;
6     q++;
7 }
```

| | | | | | | | |
|--------|--------|--------|--------|--------|--------|--------|--------|
| 0x1000 | 0x1001 | 0x1002 | 0x1003 | 0x1004 | 0x1005 | 0x1006 | 0x1007 |
| | 0x10 | 0x08 | 0x10 | 0x0E | 0x10 | 0x0A | |
| 0x1008 | 0x1009 | 0x100A | 0x100B | 0x100C | 0x100D | 0x100E | 0x100F |
| 0x00 | 0x0A | 0x00 | 0x08 | 0x12 | 0x34 | | |
| 0x1010 | 0x1011 | 0x1012 | 0x1013 | 0x1014 | 0x1015 | 0x1016 | 0x1017 |
| | | | | ... | | | |

Pointer to 'void'

```
1 int[3] a = { 10, 010, 0x1234 };
2 int* p = a;
3 void* q = a;
4 for (int i = 0; i < 3; ++i) {
5     p++;
6     q++;
7 }
```

| | | | | | | | |
|--------|--------|--------|--------|--------|--------|--------|--------|
| 0x1000 | 0x1001 | 0x1002 | 0x1003 | 0x1004 | 0x1005 | 0x1006 | 0x1007 |
| | 0x10 | 0x08 | 0x10 | 0x0E | 0x10 | 0x0B | |
| 0x1008 | 0x1009 | 0x100A | 0x100B | 0x100C | 0x100D | 0x100E | 0x100F |
| 0x00 | 0x0A | 0x00 | 0x08 | 0x12 | 0x34 | | |
| 0x1010 | 0x1011 | 0x1012 | 0x1013 | 0x1014 | 0x1015 | 0x1016 | 0x1017 |
| | | | | ... | | | |

Pointers: Observation

- A variable of pointer type just **stores an address**.
- So do variables of **array type**.
- Pointers can point to a certain type, or to **void**.
- “A pointer to void shall have the same representation and alignment requirements as a pointer to a character type.” (6.2.5.26)
- The effect of “incrementing” a pointer depends on the type pointed to.

– 2014-04 – pointers –

```
1  int a[2];
2  int* p = a;
3  ++p; // points to a[1]
4  void* q = a;
5  q += sizeof(int); // points to a[1]
6  ++q; // may point into the middle
```

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Pointer Arithmetic

– 2014-04 – pointers –

```
1  int[3] a = { 10, 010, 0x1234 }, i = 0;
2
3  int* p = a; // not &a !
4
5  if (a[0] == *p) i++; ✓
6  if (a[1] == *(p+1)) i++; ✓
7  if (a[2] == *(p+2)) i++; ✓
8
9  if (&a[2] - p == 2) i++; ✓
10
11 void* q = a;
12
13 if (a[2] == *((int*)(q + (2 * sizeof(int)))) i++; ✓
14
15 // i == 5
```

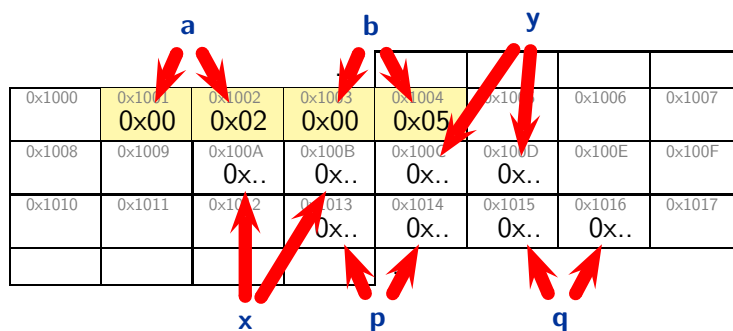
void as such does not have values, we need to **cast** 'q' here... note: **void*** can be casted to everything

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Pointers for Call By Reference

Call By Reference with Pointers

```
1 void f( int x, int y ) {  
2     x++, y++;  
3 }  
4 void g( int* p, int* q ) {  
5     (*p)++, (*q)++;  
6 }  
7 int a = 2, b = 5;  
8 f( a, b );  
9 g( &a, &b );
```



Call By Reference with Pointers

```

1 void f( int x, int y ) {
2     x++, y++;
3 }
4 void g( int* p, int* q ) {
5     (*p)++, (*q)++;
6 }
7 int a = 2, b = 5;
8 f( a, b );
9 g( &a, &b );

```

| | | | | | | | | |
|--------|--------|--------|--------|--------|--------|--------|--------|--|
| | | | | ... | | | | |
| 0x1000 | 0x1001 | 0x1002 | 0x1003 | 0x1004 | 0x1005 | 0x1006 | 0x1007 | |
| | 0x00 | 0x02 | 0x00 | 0x05 | | | | |
| 0x1008 | 0x1009 | 0x100A | 0x100B | 0x100C | 0x100D | 0x100E | 0x100F | |
| | | 0x00 | 0x02 | 0x00 | 0x05 | | | |
| 0x1010 | 0x1011 | 0x1012 | 0x1013 | 0x1014 | 0x1015 | 0x1016 | 0x1017 | |
| | | | 0x.. | 0x.. | 0x.. | 0x.. | | |
| | | | | ... | | | | |

— 2014-04 — pointers —

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Call By Reference with Pointers

```

1 void f( int x, int y ) {
2     x++, y++;
3 }
4 void g( int* p, int* q ) {
5     (*p)++, (*q)++;
6 }
7 int a = 2, b = 5;
8 f( a, b );
9 g( &a, &b );

```

| | | | | | | | | |
|--------|--------|--------|--------|--------|--------|--------|--------|--|
| | | | | ... | | | | |
| 0x1000 | 0x1001 | 0x1002 | 0x1003 | 0x1004 | 0x1005 | 0x1006 | 0x1007 | |
| | 0x00 | 0x02 | 0x00 | 0x05 | | | | |
| 0x1008 | 0x1009 | 0x100A | 0x100B | 0x100C | 0x100D | 0x100E | 0x100F | |
| | | 0x00 | 0x03 | 0x00 | 0x06 | | | |
| 0x1010 | 0x1011 | 0x1012 | 0x1013 | 0x1014 | 0x1015 | 0x1016 | 0x1017 | |
| | | | 0x.. | 0x.. | 0x.. | 0x.. | | |
| | | | | ... | | | | |

— 2014-04 — pointers —

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Call By Reference with Pointers

```

1 void f( int x, int y ) {
2     x++, y++;
3 }
4 void g( int* p, int* q ) {
5     (*p)++, (*q)++;
6 }
7 int a = 2, b = 5;
8 f( a, b );
9 g( &a, &b );

```

| | | | | | | | | |
|--------|--------|--------|--------|--------|--------|--------|--------|--|
| | | | | ... | | | | |
| 0x1000 | 0x1001 | 0x1002 | 0x1003 | 0x1004 | 0x1005 | 0x1006 | 0x1007 | |
| | 0x00 | 0x02 | 0x00 | 0x05 | | | | |
| 0x1008 | 0x1009 | 0x100A | 0x100B | 0x100C | 0x100D | 0x100E | 0x100F | |
| | | 0x.. | 0x.. | 0x.. | 0x.. | | | |
| 0x1010 | 0x1011 | 0x1012 | 0x1013 | 0x1014 | 0x1015 | 0x1016 | 0x1017 | |
| | | | 0x.. | 0x.. | 0x.. | 0x.. | | |
| | | | | ... | | | | |

— 2014-04 — pointers —

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Call By Reference with Pointers

```

1 void f( int x, int y ) {
2     x++, y++;
3 }
4 void g( int* p, int* q ) {
5     (*p)++, (*q)++;
6 }
7 int a = 2, b = 5;
8 f( a, b );
9 g( &a, &b );

```

| | | | | | | | | |
|--------|--------|--------|--------|--------|--------|--------|--------|--|
| | | | | ... | | | | |
| 0x1000 | 0x1001 | 0x1002 | 0x1003 | 0x1004 | 0x1005 | 0x1006 | 0x1007 | |
| | 0x00 | 0x02 | 0x00 | 0x05 | | | | |
| 0x1008 | 0x1009 | 0x100A | 0x100B | 0x100C | 0x100D | 0x100E | 0x100F | |
| | | 0x.. | 0x.. | 0x.. | 0x.. | | | |
| 0x1010 | 0x1011 | 0x1012 | 0x1013 | 0x1014 | 0x1015 | 0x1016 | 0x1017 | |
| | | | 0x10 | 0x01 | 0x10 | 0x03 | | |
| | | | | ... | | | | |

— 2014-04 — pointers —

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Call By Reference with Pointers

```

1 void f( int x, int y ) {
2     x++, y++;
3 }
4 void g( int* p, int* q ) {
5     (*p)++, (*q)++;
6 }
7 int a = 2, b = 5;
8 f( a, b );
9 g( &a, &b );

```

| | | | | | | | | |
|--------|--------|--------|--------|--------|--------|--------|--------|--|
| | | | | ... | | | | |
| 0x1000 | 0x1001 | 0x1002 | 0x1003 | 0x1004 | 0x1005 | 0x1006 | 0x1007 | |
| | 0x00 | 0x03 | 0x00 | 0x06 | | | | |
| 0x1008 | 0x1009 | 0x100A | 0x100B | 0x100C | 0x100D | 0x100E | 0x100F | |
| | | 0x.. | 0x.. | 0x.. | 0x.. | | | |
| 0x1010 | 0x1011 | 0x1012 | 0x1013 | 0x1014 | 0x1015 | 0x1016 | 0x1017 | |
| | | | 0x10 | 0x01 | 0x10 | 0x03 | | |
| | | | | ... | | | | |

Call By Reference with Pointers

```

1 void f( int x, int y ) {
2     x++, y++;
3 }
4 void g( int* p, int* q ) {
5     (*p)++, (*q)++;
6 }
7 int a = 2, b = 5;
8 f( a, b );
9 g( &a, &b );

```

| | | | | | | | | |
|--------|--------|--------|--------|--------|--------|--------|--------|--|
| | | | | ... | | | | |
| 0x1000 | 0x1001 | 0x1002 | 0x1003 | 0x1004 | 0x1005 | 0x1006 | 0x1007 | |
| | 0x00 | 0x03 | 0x00 | 0x06 | | | | |
| 0x1008 | 0x1009 | 0x100A | 0x100B | 0x100C | 0x100D | 0x100E | 0x100F | |
| | | 0x.. | 0x.. | 0x.. | 0x.. | | | |
| 0x1010 | 0x1011 | 0x1012 | 0x1013 | 0x1014 | 0x1015 | 0x1016 | 0x1017 | |
| | | | 0x.. | 0x.. | 0x.. | 0x.. | | |
| | | | | ... | | | | |

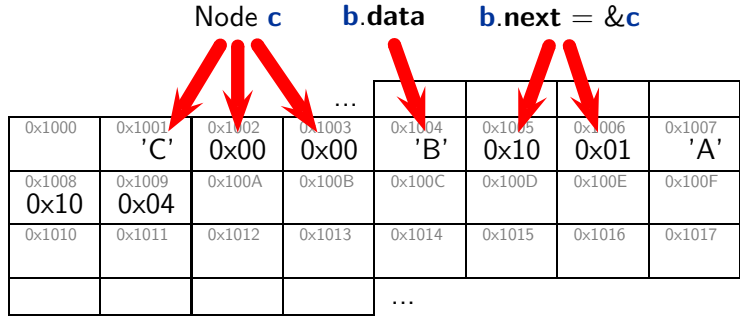
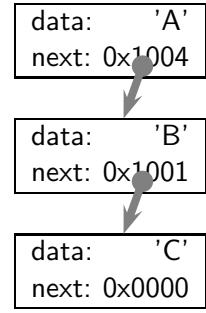
Dynamic Storage & Storage Duration

Dynamic Storage Allocation

A Linked List

```

1 typedef struct Node {
2     char data;
3     struct Node* next;
4 } Node;
5
6 Node c = { 'C', 0 };
7 Node b = { 'B', &c };
8 Node a = { 'A', &b };
    
```



Dynamic Storage Allocation

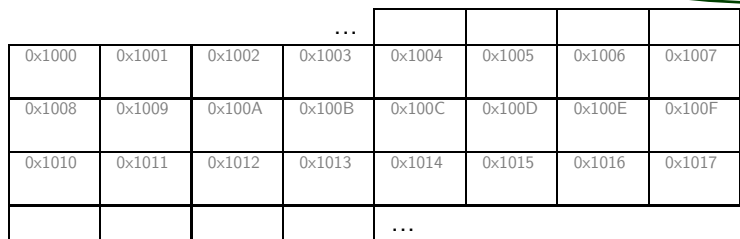
```

1 typedef struct Node {
2     char data; struct Node* next; } Node;
3
4 Node *head = 0, *hlp;
5
6 void insert( char d ) {
7     hlp = (Node*) malloc( sizeof(Node) );
8     hlp->data = d;
9     hlp->next = head;
10    head = hlp;
11 }
12
13 insert( 'C' );
14 insert( 'B' );
15 insert( 'A' );
    
```

"mem. allocate"

allocate some space for a **Node**, return its address; may fail ("out of memory"), malloc(3) yields 0 then

was part reference section



Dynamic Storage Allocation

```
1 typedef struct Node {
2     char data; struct Node* next; } Node;
3
4 Node *head = 0, *hlp;
5
6 void insert( char d ) {
7     hlp = (Node*)malloc( sizeof(Node) );
8     hlp->data = d;
9     hlp->next = head;
10    head = hlp;
11 }
12
13 insert( 'C' );
14 insert( 'B' );
15 insert( 'A' );
```

head

| | | | | | | | | |
|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| 0x1000 | 0x1001 | 0x1002 | ... | 0x1003 | 0x1004 | 0x1005 | 0x1006 | 0x1007 |
| 0x1008 | 0x1009 | 0x100A | 0x100B | 0x100C | 0x100D | 0x100E | 0x100F | |
| 0x1010 | 0x1011 | 0x1012 | 0x1013 | 0x1014 | 0x1015 | 0x1016 | 0x1017 | |
| | | | | ... | | | | |

Note: In the original image, red arrows point from the word 'head' to the 0x1001 and 0x1002 cells in the first row of the memory table.

— 2014-04 — storage —

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Dynamic Storage Allocation

```
1 typedef struct Node {
2     char data; struct Node* next; } Node;
3
4 Node *head = 0, *hlp;
5
6 void insert( char d ) {
7     hlp = (Node*)malloc( sizeof(Node) );
8     hlp->data = d;
9     hlp->next = head;
10    head = hlp;
11 }
12
13 insert( 'C' );
14 insert( 'B' );
15 insert( 'A' );
```

| | | | | | | | | |
|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| 0x1000 | 0x1001 | 0x1002 | ... | 0x1003 | 0x1004 | 0x1005 | 0x1006 | 0x1007 |
| 0x1008 | 0x1009 | 0x100A | 0x100B | 0x100C | 0x100D | 0x100E | 0x100F | |
| 0x1010 | 0x1011 | 0x1012 | 0x1013 | 0x1014 | 0x1015 | 0x1016 | 0x1017 | |
| | | | | ... | | | | |

Note: In the original image, a green arrow points to the 0x1001 cell in the first row of the memory table.

— 2014-04 — storage —

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Dynamic Storage Allocation

```

1  typedef struct Node {
2      char data; struct Node* next; } Node;
3
4  Node *head = 0, *hlp;
5
6  void insert( char d ) {
7      hlp = (Node*)malloc( sizeof(Node) );
8      hlp->data = d;
9      hlp->next = head;
10     head = hlp;
11 }
12
13 insert( 'C' );
14 insert( 'B' );
15 insert( 'A' );

```

hlp

| | | | | | | | |
|--------|--------|--------|--------|--------|--------|--------|--------|
| 0x1000 | 0x1001 | 0x1002 | 0x1003 | 0x1004 | 0x1005 | 0x1006 | 0x1007 |
| | 0x00 | 0x00 | 0x10 | 0x13 | | | |
| 0x1008 | 0x1009 | 0x100A | 0x100B | 0x100C | 0x100D | 0x100E | 0x100F |
| 0x1010 | 0x1011 | 0x1012 | 0x1013 | 0x1014 | 0x1015 | 0x1016 | 0x1017 |
| | | | '..' | 0x.. | 0x.. | | |
| | | | | ... | | | |

— 2014-04 — storage —

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Dynamic Storage Allocation

```

1  typedef struct Node {
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13 insert( 'C' );
14 insert( 'B' );
15 insert( 'A' );

```

| | | | | | | | |
|--------|--------|--------|--------|--------|--------|--------|--------|
| | | | ... | | | | |
| 0x1000 | 0x1001 | 0x1002 | 0x1003 | 0x1004 | 0x1005 | 0x1006 | 0x1007 |
| | 0x00 | 0x00 | 0x10 | 0x13 | | | |
| 0x1008 | 0x1009 | 0x100A | 0x100B | 0x100C | 0x100D | 0x100E | 0x100F |
| 0x1010 | 0x1011 | 0x1012 | 0x1013 | 0x1014 | 0x1015 | 0x1016 | 0x1017 |
| | | | 'C' | 0x.. | 0x.. | | |
| | | | | ... | | | |

— 2014-04 — storage —

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Dynamic Storage Allocation

```

1  typedef struct Node {
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11 }
12
13 insert( 'C' );
14 insert( 'B' );
15 insert( 'A' );

```

...

| | | | | | | | |
|--------|--------|--------|--------|--------|--------|--------|--------|
| 0x1000 | 0x1001 | 0x1002 | 0x1003 | 0x1004 | 0x1005 | 0x1006 | 0x1007 |
| | 0x00 | 0x00 | 0x10 | 0x13 | | | |
| 0x1008 | 0x1009 | 0x100A | 0x100B | 0x100C | 0x100D | 0x100E | 0x100F |
| 0x1010 | 0x1011 | 0x1012 | 0x1013 | 0x1014 | 0x1015 | 0x1016 | 0x1017 |
| | | | 'C' | 0x00 | 0x00 | | |
| | | | | ... | | | |

- 2014-04 - storage -

57/125

Dynamic Storage Allocation

```

1  typedef struct Node {
2      char data; struct Node* next; } Node;
3
4  Node *head = 0, *hlp;
5
6  void insert( char d ) {
7      hlp = (Node*)malloc( sizeof(Node) );
8      hlp->data = d;
9      hlp->next = head;
10     head = hlp;
11 }
12
13 insert( 'C' );
14 insert( 'B' );
15 insert( 'A' );

```

...

| | | | | | | | |
|--------|--------|--------|--------|--------|--------|--------|--------|
| 0x1000 | 0x1001 | 0x1002 | 0x1003 | 0x1004 | 0x1005 | 0x1006 | 0x1007 |
| | 0x10 | 0x13 | 0x10 | 0x13 | | | |
| 0x1008 | 0x1009 | 0x100A | 0x100B | 0x100C | 0x100D | 0x100E | 0x100F |
| 0x1010 | 0x1011 | 0x1012 | 0x1013 | 0x1014 | 0x1015 | 0x1016 | 0x1017 |
| | | | 'C' | 0x00 | 0x00 | | |
| | | | | ... | | | |

- 2014-04 - storage -

57/125

Dynamic Storage Allocation

```

1  typedef struct Node {
2      char data; struct Node* next; } Node;
3
4  Node *head = 0, *hlp;
5
6  void insert( char d ) {
7      hlp = (Node*)malloc( sizeof(Node) );
8      hlp->data = d;
9      hlp->next = head;
10     head = hlp;
11 }
12
13 insert( 'C' );
14 insert( 'B' );
15 insert( 'A' );

```

| |
|--------------|
| data: 'C' |
| next: 0x0000 |

...

| | | | | | | | |
|--------|--------|--------|--------|--------|--------|--------|--------|
| 0x1000 | 0x1001 | 0x1002 | 0x1003 | 0x1004 | 0x1005 | 0x1006 | 0x1007 |
| | 0x10 | 0x13 | 0x10 | 0x13 | | | |
| 0x1008 | 0x1009 | 0x100A | 0x100B | 0x100C | 0x100D | 0x100E | 0x100F |
| 0x1010 | 0x1011 | 0x1012 | 0x1013 | 0x1014 | 0x1015 | 0x1016 | 0x1017 |
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Dynamic Storage Allocation

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|--------------|
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| next: 0x0000 |

...

| | | | | | | | |
|--------|--------|--------|--------|--------|--------|--------|--------|
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57/125

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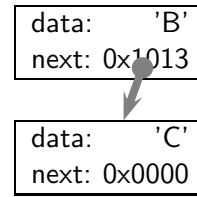
57/125

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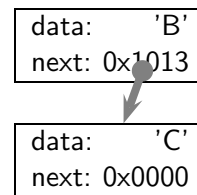
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|--------|--------|--------|--------|--------|--------|--------|--------|
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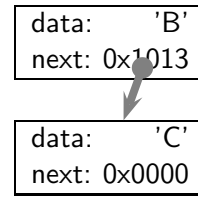
| | | | | | | | |
|--------|--------|--------|--------|--------|--------|--------|--------|
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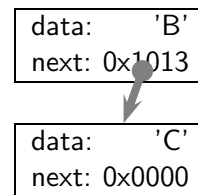
57/125

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— 2014-04 — storage —

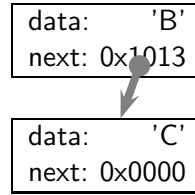
57/125

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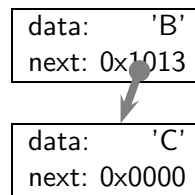
57/125

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— 2014-04 — storage —

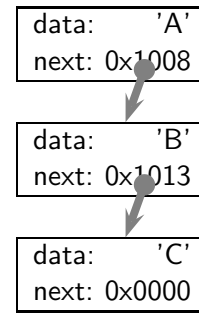
57/125

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Dynamic Storage Management

Dynamic Storage Allocation:

- void* **malloc**(**size_t** size);
“[...] allocates **size** bytes and returns a pointer to the allocated memory.
The memory is not initialized. [...]”
- “On error, [this function] returns NULL.”
- void **free**(void* ptr)
“[...] frees the memory space pointed to by **ptr**, which **must** have been returned by a previous call to malloc(), [...]”
- “Otherwise, or if **free(ptr)** has already been called before, **undefined behavior** occurs.”
- “If **ptr** is **NULL**, no operation is performed.”
- **No garbage collection!**
Management of dynamic storage is **responsibility of the programmer**.
Unaccessible, not free'd memory is called **memory leak**.

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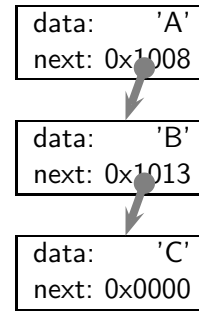
58/125

Dynamic Storage Management Example

```

1 void remove() {
2     if (hlp = head) {
3         head = hlp->next;
4         free(hlp);
5     }
6 }
7 insert( 'C' ); insert( 'B' ); insert( 'A' );
8 remove();
9 insert( 'X' );

```



| | | | | | | | |
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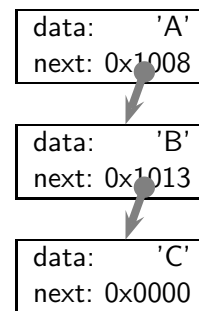
59/125

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— 2014-04 — storage —

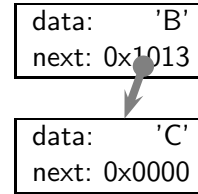
59/125

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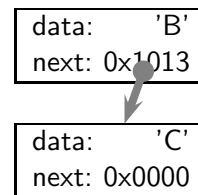
59/125

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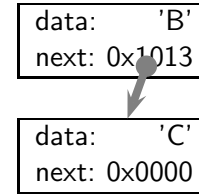
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— 2014-04 — storage —

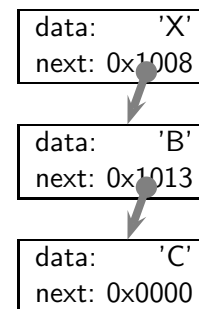
59/125

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— 2014-04 — storage —

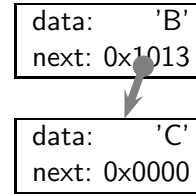
59/125

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9 insert( 'X' );

```



| | | | | | | | |
|--------|--------|--------|--------|--------|--------|--------|--------|
| 0x1000 | 0x1001 | 0x1002 | ... | 0x1004 | 0x1005 | 0x1006 | 0x1007 |
| | 0x10 | 0x08 | 0x10 | 0x0D | | | |
| 0x1008 | 0x1009 | 0x100A | 0x100B | 0x100C | 0x100D | 0x100E | 0x100F |
| 'B' | 0x10 | 0x13 | | | 'A' | 0x10 | 0x08 |
| 0x1010 | 0x1011 | 0x1012 | 0x1013 | 0x1014 | 0x1015 | 0x1016 | 0x1017 |
| 'X' | 0x10 | 0x08 | 'C' | 0x00 | 0x00 | | |
| | | | | ... | | | |

— 2014-04 — storage —

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Dynamic Linked List Iteration

```

1 Node* find( char d ) {
2     hlp = head;
3     while (hlp) {
4         if (hlp->data == d)
5             break;
6         hlp = hlp->next;
7     }
8     return hlp;
9 }
10 insert( 'C' ); insert( 'B' ); insert( 'A' );
11 find( 'B' ); // yields 0x1008
12 find( 'O' ); // yields 0x0000, aka. NULL

```

| | | | | | | | |
|--------|--------|--------|--------|--------|--------|--------|--------|
| 0x1000 | 0x1001 | 0x1002 | ... | 0x1004 | 0x1005 | 0x1006 | 0x1007 |
| | 0x10 | 0x0D | 0x10 | 0x0D | | | |
| 0x1008 | 0x1009 | 0x100A | 0x100B | 0x100C | 0x100D | 0x100E | 0x100F |
| 'B' | 0x10 | 0x13 | | | 'A' | 0x10 | 0x08 |
| 0x1010 | 0x1011 | 0x1012 | 0x1013 | 0x1014 | 0x1015 | 0x1016 | 0x1017 |
| | | | 'C' | 0x00 | 0x00 | | |
| | | | | ... | | | |

— 2014-04 — storage —

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Pointers to Struct/Union — ‘.’ vs. ‘->’

```
1  typedef struct {
2      int x;
3      int y;
4  } coordinate;
5
6  coordinate pos = { 13, 27 };
7
8  coordinate* p = &pos;
9
10 int tmp; tmp = pos.x;
11
12 tmp = (*p).x;
13 (*p).x = (*p).y;
14 (*p).y = tmp;
15
16 tmp = p->x;
17 p->x = p->y;
18 p->y = tmp;
```

Storage Duration of Objects

Storage Duration of Objects (6.2.4)

- **“static”** – e.g. variables in program scope:
 - live from program start to end
 - if not explicitly initialized, set to 0 (6.7.8)
- **“automatic”** – non-static variables in local scope:
 - live from block entry to exit
 - not automatically initialised: “initial value [...] is indeterminate”
- **“allocated”** – dynamic objects:
 - live from **malloc** to **free**
 - not automatically initialised

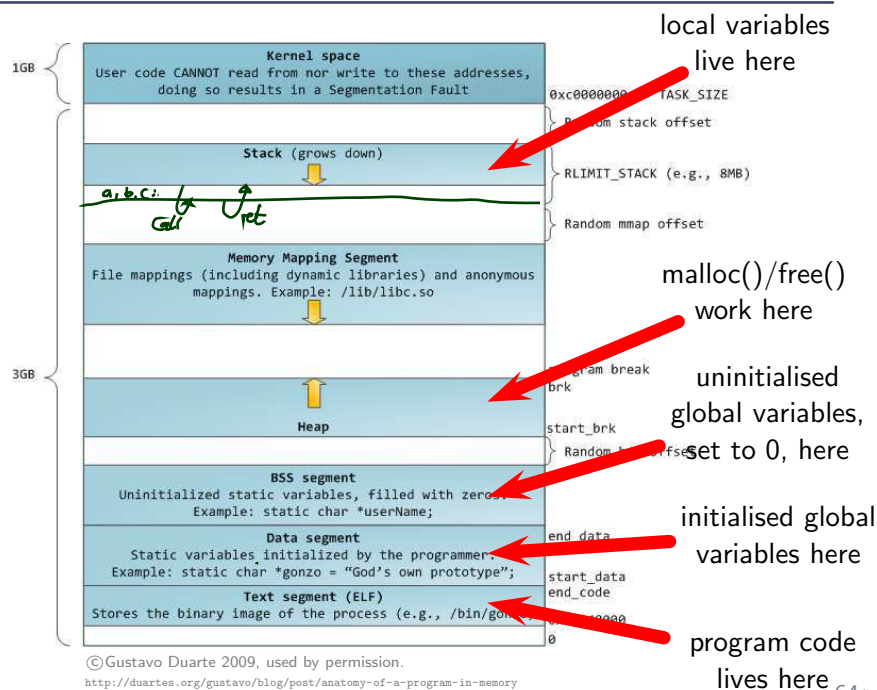
“If an object is referred to outside of its lifetime, **the behavior is undefined**.

The value of a pointer becomes indeterminate when the object it points to reaches the end of its lifetime.”

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Example: Anatomy of a Linux Program in Memory



– 2014-04 – storage –

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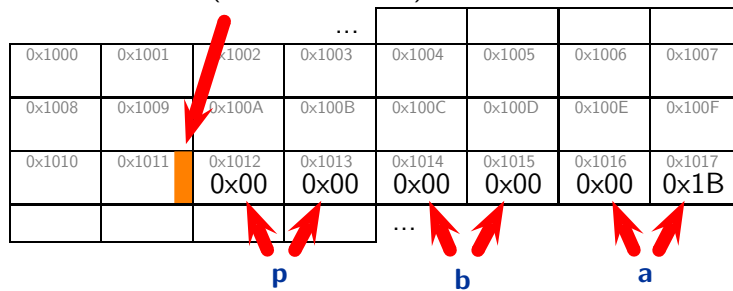
Storage Duration “Automatic” (Simplified)

```

1 void h() { int y; y++; }
2 void g() { int x = 5; x++; }
3 int* f() { int c = 3; g(); h(); h(); return &c; }
4
5 int a = 27, b, *p;
6 p = f();
7 b = *p;

```

stack pointer – stack ends at
0x1012 in this case; stack grows
downwards (to smaller addr.)



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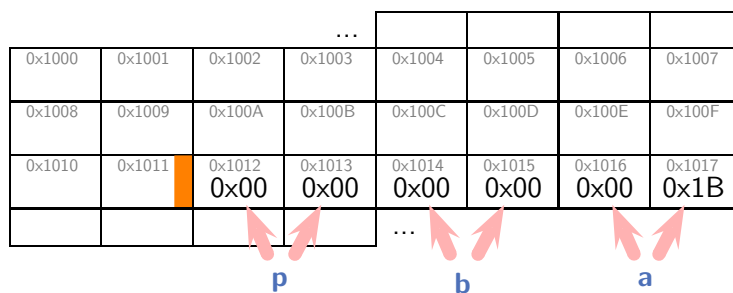
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Storage Duration “Automatic” (Simplified)

```

1 void h() { int y; y++; }
2 void g() { int x = 5; x++; }
3 int* f() { int c = 3; g(); h(); h(); return &c; }
4
5 int a = 27, b, *p;
6 p = f();
7 b = *p;

```



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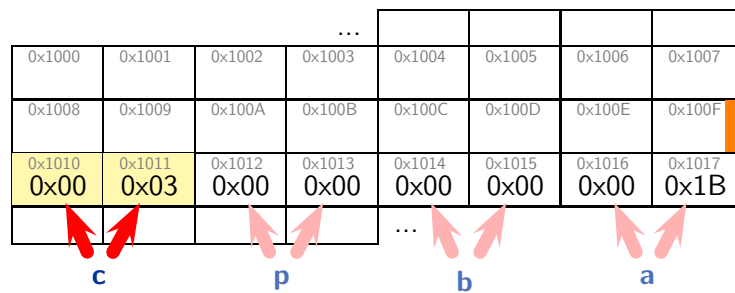
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Storage Duration “Automatic” (Simplified)

```

1 void h() { int y; y++; }
2 void g() { int x = 5; x++; }
3 int* f() { int c = 3; g(); h(); h(); return &c; }
4
5 int a = 27, b, *p;
6 p = f();
7 b = *p;

```



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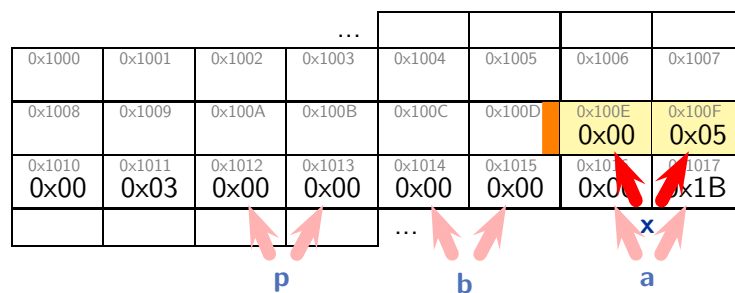
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Storage Duration “Automatic” (Simplified)

```

1 void h() { int y; y++; }
2 void g() { int x = 5; x++; }
3 int* f() { int c = 3; g(); h(); h(); return &c; }
4
5 int a = 27, b, *p;
6 p = f();
7 b = *p;

```



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Storage Duration “Automatic” (Simplified)

```

1 void h() { int y; y++; }
2 void g() { int x = 5; x++; }
3 int* f() { int c = 3; g(); h(); h(); return &c; }
4
5 int a = 27, b, *p;
6 p = f();
7 b = *p;
    
```

...

| | | | | | | | |
|--------|--------|--------|--------|--------|--------|----------------|----------------|
| 0x1000 | 0x1001 | 0x1002 | 0x1003 | 0x1004 | 0x1005 | 0x1006 | 0x1007 |
| 0x1008 | 0x1009 | 0x100A | 0x100B | 0x100C | 0x100D | 0x100E 0x00 | 0x100F 0x06 |
| 0x1010 | 0x1011 | 0x1012 | 0x1013 | 0x1014 | 0x1015 | 0x1016 | 0x1017 |
| 0x00 | 0x03 | 0x00 | 0x00 | 0x00 | 0x00 | 0x00 | 0x1B |
| | | | | ... | | | |

p
b
a

- 2014-04 - storage -

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Storage Duration “Automatic” (Simplified)

```

1 void h() { int y; y++; }
2 void g() { int x = 5; x++; }
3 int* f() { int c = 3; g(); h(); h(); return &c; }
4
5 int a = 27, b, *p;
6 p = f();
7 b = *p;
    
```

...

| | | | | | | | |
|--------|--------|--------|--------|--------|--------|----------------|----------------|
| 0x1000 | 0x1001 | 0x1002 | 0x1003 | 0x1004 | 0x1005 | 0x1006 | 0x1007 |
| 0x1008 | 0x1009 | 0x100A | 0x100B | 0x100C | 0x100D | 0x100E 0x00 | 0x100F 0x06 |
| 0x1010 | 0x1011 | 0x1012 | 0x1013 | 0x1014 | 0x1015 | 0x1016 | 0x1017 |
| 0x00 | 0x03 | 0x00 | 0x00 | 0x00 | 0x00 | 0x00 | 0x1B |
| | | | | ... | | | |

p
b
a

x no longer alive!

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65/125

Storage Duration “Automatic” (Simplified)

```

1 void h() { int y; y++; }
2 void g() { int x = 5; x++; }
3 int* f() { int c = 3; g(); h(); h(); return &c; }
4
5 int a = 27, b, *p;
6 p = f();
7 b = *p;
    
```

(now) **y** – not explicitly initialised, thus initial value is indeterminate

...

| | | | | | | | |
|--------|--------|--------|--------|--------|--------|--------|--------|
| 0x1000 | 0x1001 | 0x1002 | 0x1003 | 0x1004 | 0x1005 | 0x1006 | 0x1007 |
| 0x1008 | 0x1009 | 0x100A | 0x100B | 0x100C | 0x100D | 0x100E | 0x100F |
| 0x1010 | 0x1011 | 0x1012 | 0x1013 | 0x1014 | 0x1015 | 0x1016 | 0x1017 |
| 0x00 | 0x03 | 0x00 | 0x00 | 0x00 | 0x00 | 0x00 | 0x1B |
| | | | | ... | | | |

p
b
a

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Storage Duration “Automatic” (Simplified)

```

1 void h() { int y; y++; }
2 void g() { int x = 5; x++; }
3 int* f() { int c = 3; g(); h(); h(); return &c; }
4
5 int a = 27, b, *p;
6 p = f();
7 b = *p;
    
```

...

| | | | | | | | |
|--------|--------|--------|--------|--------|--------|--------|--------|
| 0x1000 | 0x1001 | 0x1002 | 0x1003 | 0x1004 | 0x1005 | 0x1006 | 0x1007 |
| 0x1008 | 0x1009 | 0x100A | 0x100B | 0x100C | 0x100D | 0x100E | 0x100F |
| 0x1010 | 0x1011 | 0x1012 | 0x1013 | 0x1014 | 0x1015 | 0x1016 | 0x1017 |
| 0x00 | 0x03 | 0x00 | 0x00 | 0x00 | 0x00 | 0x00 | 0x1B |
| | | | | ... | | | |

p
b
a

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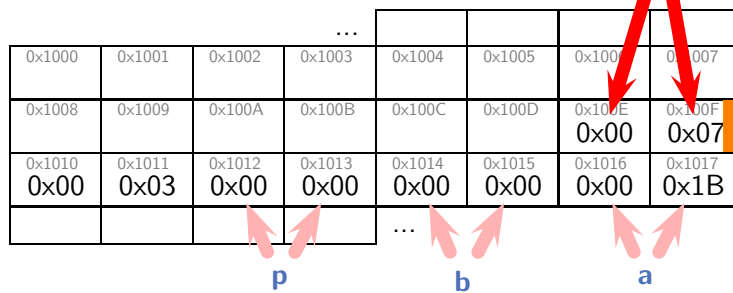
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Storage Duration “Automatic” (Simplified)

```

1 void h() { int y; y++; }
2 void g() { int x = 5; x++; }
3 int* f() { int c = 3; g(); h(); h(); return &c; }
4
5 int a = 27, b, *p;
6 p = f();
7 b = *p;
    
```

y no longer alive!



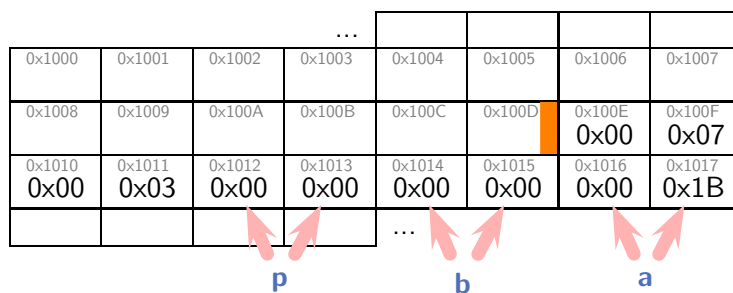
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65/125

Storage Duration “Automatic” (Simplified)

```

1 void h() { int y; y++; }
2 void g() { int x = 5; x++; }
3 int* f() { int c = 3; g(); h(); h(); return &c; }
4
5 int a = 27, b, *p;
6 p = f();
7 b = *p;
    
```



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Storage Duration “Automatic” (Simplified)

```

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2 void g() { int x = 5; x++; }
3 int* f() { int c = 3; g(); h(); h(); return &c; }
4
5 int a = 27, b, *p;
6 p = f();
7 b = *p;
    
```

...

| | | | | | | | |
|--------|--------|--------|--------|--------|--------|----------------|----------------|
| 0x1000 | 0x1001 | 0x1002 | 0x1003 | 0x1004 | 0x1005 | 0x1006 | 0x1007 |
| 0x1008 | 0x1009 | 0x100A | 0x100B | 0x100C | 0x100D | 0x100E 0x00 | 0x100F 0x08 |
| 0x1010 | 0x1011 | 0x1012 | 0x1013 | 0x1014 | 0x1015 | 0x1016 | 0x1017 |
| 0x00 | 0x03 | 0x00 | 0x00 | 0x00 | 0x00 | 0x00 | 0x1B |
| | | | | ... | | | |

p
b
a

- 2014-04 - storage -

65/125

Storage Duration “Automatic” (Simplified)

```

1 void h() { int y; y++; }
2 void g() { int x = 5; x++; }
3 int* f() { int c = 3; g(); h(); h(); return &c; }
4
5 int a = 27, b, *p;
6 p = f();
7 b = *p;
    
```

...

| | | | | | | | |
|--------|--------|--------|--------|--------|--------|----------------|----------------|
| 0x1000 | 0x1001 | 0x1002 | 0x1003 | 0x1004 | 0x1005 | 0x1006 | 0x1007 |
| 0x1008 | 0x1009 | 0x100A | 0x100B | 0x100C | 0x100D | 0x100E 0x00 | 0x100F 0x08 |
| 0x1010 | 0x1011 | 0x1012 | 0x1013 | 0x1014 | 0x1015 | 0x1016 | 0x1017 |
| 0x00 | 0x03 | 0x00 | 0x00 | 0x00 | 0x00 | 0x00 | 0x1B |
| | | | | ... | | | |

p
b
a

- 2014-04 - storage -

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Storage Duration “Automatic” (Simplified)

```

1 void h() { int y; y++; }
2 void g() { int x = 5; x++; }
3 int* f() { int c = 3; g(); h(); h(); return &c; }
4
5 int a = 27, b, *p;
6 p = f();
7 b = *p;
    
```

...

| | | | | | | | |
|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| 0x1000 | 0x1001 | 0x1002 | 0x1003 | 0x1004 | 0x1005 | 0x1006 | 0x1007 |
| 0x1008 | 0x1009 | 0x100A | 0x100B | 0x100C | 0x100D | 0x100E 0x00 | 0x100F 0x08 |
| 0x1010 0x00 | 0x1011 0x03 | 0x1012 0x00 | 0x1013 0x00 | 0x1014 0x00 | 0x1015 0x00 | 0x1016 0x00 | 0x1017 0x1B |
| | | | | ... | | | |

p
b
a

- 2014-04 - storage -

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Storage Duration “Automatic” (Simplified)

```

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```

...

| | | | | | | | |
|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| 0x1000 | 0x1001 | 0x1002 | 0x1003 | 0x1004 | 0x1005 | 0x1006 | 0x1007 |
| 0x1008 | 0x1009 | 0x100A | 0x100B | 0x100C | 0x100D | 0x100E 0x00 | 0x100F 0x08 |
| 0x1010 0x00 | 0x1011 0x03 | 0x1012 0x10 | 0x1013 0x10 | 0x1014 0x00 | 0x1015 0x00 | 0x1016 0x00 | 0x1017 0x1B |
| | | | | ... | | | |

p
b
a

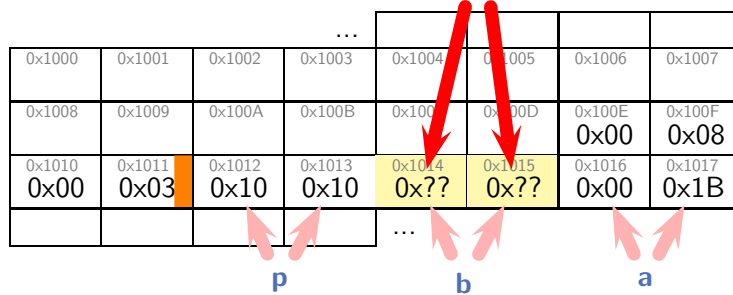
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Storage Duration “Automatic” (Simplified)

```
1 void h() { int y; y++; }
2 void g() { int x = 5; x++; }
3 int* f() { int c = 3; g(); h(); h(); return &c; }
4
5 int a = 27, b, *p;
6 p = f();
7 b = *p;
```

p refers to a non-alive object, the behavior is undefined (everything **may happen**, from ‘crash’ to ‘ignore’).



— 2014-04 — storage —

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Storage Classes and Qualifiers

— 2014-04 — modifiers —

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Storage Class Specifiers (6.7.1)

Storage Class Specifiers (6.7.1)

```
1 typedef char letter;  
2  
3 extern int x;  
4 extern int f();  
5  
6 // static int x; // two uses! (-> later)  
7 // static int f();  
8  
9  
10 int auto x; // "historic"  
11  
12 int register y; // "historic"
```

Storage Class Specifiers: *extern* (6.7.1)

```
1 // not _defined_ here, "imported" ...
2 //
3 extern int x;
4 extern void f();
5
6 // declared _and_ defined here, "exported" ...
7 //
8 int y;
9
10 int g() {
11     x = y = 27;
12     f();
13 }
```

– 2014-04 – modifiers –

- → modules, linking (later)
- usually only *extern* in headers (later)

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Storage Class Specifiers: *static* (6.7.1)

```
1 // declared _and_ defined here,
2 // _not_ "exported" ...
3 //
4 static int x;
5 static void g();
6
7
8 int f() {
9     static int a = 0;
10    a++;
11    printf( "%s\n", a );
12 }
13
14 f(); f(); f(); // yields 1, 2, 3
```

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Qualifiers (6.7.3)

Qualifiers (6.7.3)

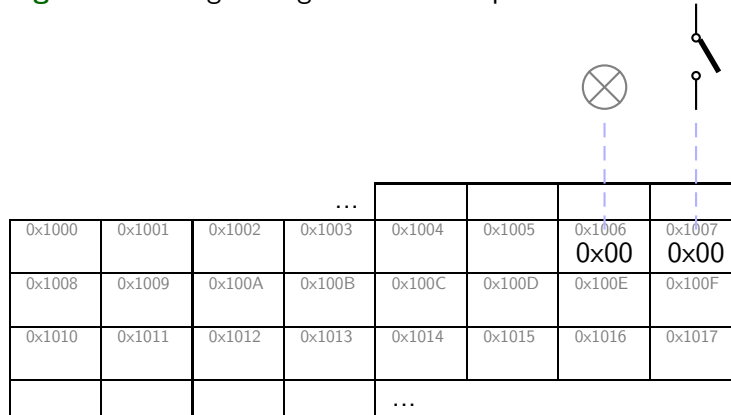
```
1 int x;  
2  
3 const int y;  
4  
5 volatile int z;  
6  
7 int* restrict p; // aliasing  
8  
9  
10 const volatile int a;
```

restrict:

- “[... lengthy formal definition ...]”
- “[...] If these requirements are not met, then the behavior is **undefined**.”
- → use **extremely carefully** (i.e. if in doubt, not at all)

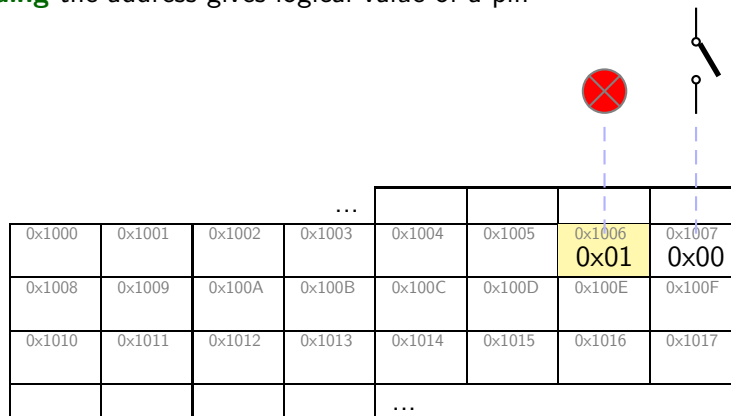
Excursion: Memory Mapped I/O

- **Intuition:** some memory addresses are wired to hardware
 - **writing** to the address causes a pin to change logical value
 - **reading** the address gives logical value of a pin



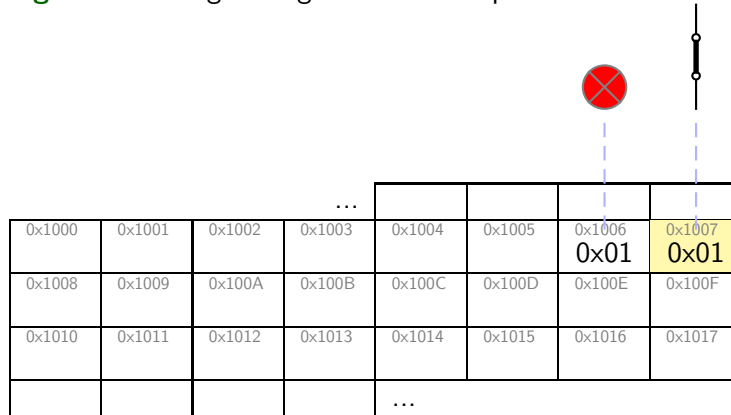
Excursion: Memory Mapped I/O

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Excursion: Memory Mapped I/O

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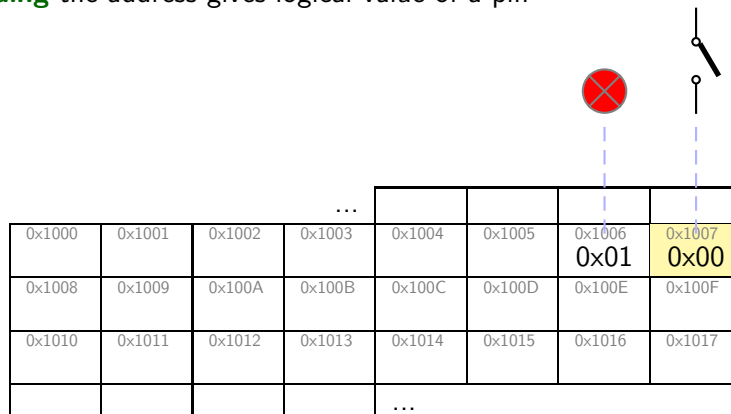


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Excursion: Memory Mapped I/O

- **Intuition:** some memory addresses are wired to hardware
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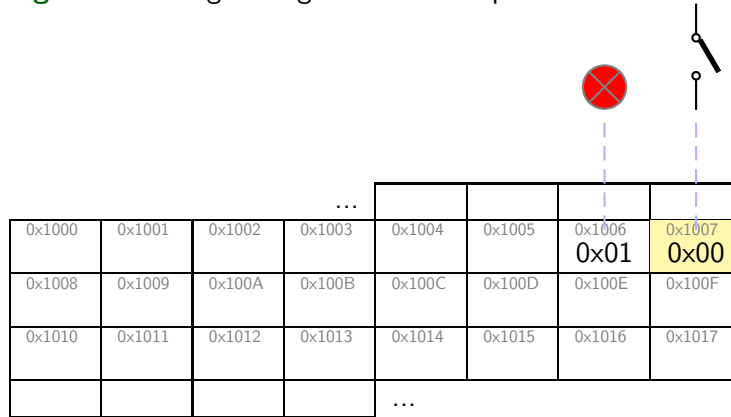


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Excursion: Memory Mapped I/O

- **Intuition:** some memory addresses are wired to hardware
 - **writing** to the address causes a pin to change logical value
 - **reading** the address gives logical value of a pin



- The compiler does not know, “**memory is memory**”.

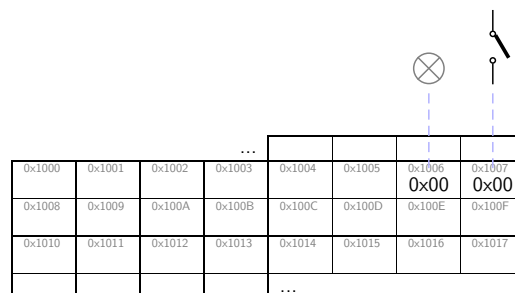
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Qualifiers: *volatile* (6.7.3)

```

1 volatile char* out = 0x1006;
2 volatile char* in = 0x1007;
3
4 *out = 0x01; // switch lamp on
5
6 if (*in & 0x01) { /* ... */ }
7
8 if ((*in & 0x01) && (*in & 0x01)) { /* ... */ }
```



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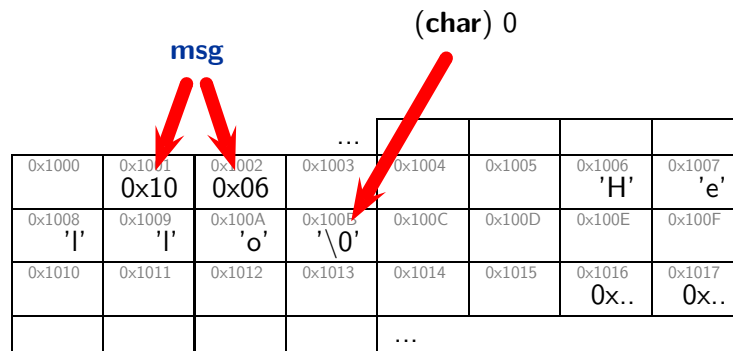
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Strings & Input/Output

Strings

Strings are 0-Terminated *char* Arrays

```
1 char* msg = "Hello";  
2 char* str = msg;
```

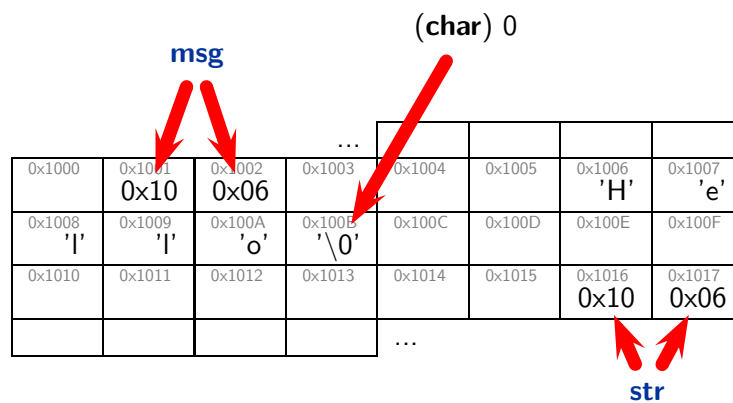


- 2014-04 - stringsandio -

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Strings are 0-Terminated *char* Arrays

```
1 char* msg = "Hello";  
2 char* str = msg;
```



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String Manipulation (Annex B)

include<string.h>

provides among others:

- size_t **strlen**(const char* s)
“[...] calculates length of string s, excluding **the terminating null byte** ('\0).”
- int **strcmp**(const char* s1, const char* s2)
“[...] compares the two strings s1 and s2.
It returns an integer less than, equal to, or greater than zero if s1 is found, respectively, to be less than, to match, or be greater than s2.”
- char* **strcpy**(char* s1, const char* s2)
“The strcpy() function copies the string pointed to by s2, including **the terminating null byte** ('\0'), to the buffer pointed to by s1.”
- char* **strncpy**(char* s1, const char* s2, size_t n)

None of these functions allocates memory!

Allocate and copy: (not C99, but POSIX)

- char* **strdup**(const char* s)

Input/Output

Printing

```
1 #include <stdio.h>
2
3 printf( "%s %i %f\n", "Hello", 27, 3.14 );
```

formatted
string
integer
(or d)
float
newline

Tools & Modules

Hello, Again

```
1 #include <stdio.h>
2
3 int g( int x ) { return x/2; }
4
5 int f() { return g(1); }
6
7 int main() {
8     printf( "Hello World.\n" );
9     return f();
10 }
```

- % gcc helloworld.c
- % ls
- a.out helloworld.c
- % ./a.out
- Hello World.
- %

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Zoom In: Preprocessing, Compiling, Linking

```
1 #include <stdio.h>
2
3 int g( int x ) { return x/2; }
4
5 int f() { return g(1); }
6
7 int main() {
8     printf( "Hello World.\n" );
9     return f();
10 }
```

- % gcc -E helloworld.c > helloworld.i
- % gcc -c -o helloworld.o helloworld.c
- % ld -o helloworld [...] helloworld.o [...]
- % ./helloworld
- Hello World.
- %

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Modules

```
1 #include <stdio.h>
2
3 int g( int x ) {
4     return x/2;
5 }
6
7 int f() {
8     return g(1);
9 }
10
11 int main() {
12     printf( "Hello World.\n" );
13     return f();
14 }
```

-
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-

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Modules

```
1 #include <stdio.h>
2
3 int g( int x ) {
4     return x/2;
5 }
6
7 int f() {
8     return g(1);
9 }
10
11 int main() {
12     printf( "Hello World.\n" );
13     return f();
14 }
```

Split into:

- .h (header): declarations
- .c: definitions, use headers to “import” declarations

-
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-

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Modules

```
1 #include <stdio.h>
2
3 int g( int x ) {
4     return x/2;
5 }
6
7 int f() {
8     return g(1);
9 }
10
11 int main() {
12     printf( "Hello World.\n" );
13     return f();
14 }
```

```
g.h
1 #ifndef G_H
2 #define G_H
3
4 extern int
5     g( int x );
6 #endif
```

```
f.h
1 #ifndef F_H
2 #define F_H
3
4 extern int
5     f();
6 #endif
```

```
g.c
1 #include "g.h"
2
3 int g( int x ) {
4     return x/2;
5 }
```

```
f.c
1 #include "g.h"
2 #include "f.h"
3
4 int f() {
5     return g(1);
6 }
```

Split into:

- .h (header): declarations
- .c: definitions, use headers to "import" declarations

```
helloworld.c
1 #include <stdio.h>
2 #include "f.h"
3
4 int main() {
5     printf( "Hello World.\n" );
6     return f();
7 }
```

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Modules At Work

preprocess & compile:

- % gcc -c g.c f.c \ helloworld.c
- % ls *.o
- f.o g.o helloworld.o

link:

- % gcc g.o f.o helloworld.o

execute:

- % ./a.out
- Hello World.

```
g.h
1 #ifndef G_H
2 #define G_H
3
4 extern int
5     g( int x );
6 #endif
```

```
f.h
1 #ifndef F_H
2 #define F_H
3
4 extern int
5     f();
6 #endif
```

```
g.c
1 #include "g.h"
2
3 int g( int x ) {
4     return x/2;
5 }
```

```
f.c
1 #include "g.h"
2 #include "f.h"
3
4 int f() {
5     return g(1);
6 }
```

```
helloworld.c
1 #include <stdio.h>
2 #include "f.h"
3
4 int main() {
5     printf( "Hello World.\n" );
6     return f();
7 }
```

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Modules At Work

preprocess & compile:

- `% gcc -c g.c f.c \ helloworld.c`
- `% ls *.o`
- `f.o g.o helloworld.o`

link:

- `% gcc g.o f.o helloworld.o`

execute:

- `% ./a.out`
- Hello World.

```
g.h
1 #ifndef G_H
2 #define G_H
3
4 extern int
5   g( int x );
6 #endif

f.h
1 #ifndef F_H
2 #define F_H
3
4 extern int
5   f();
6 #endif
```

```
g.c
1 #include "g.h"
2
3 int g( int x ) {
4   return x/2;
5 }

f.c
1 #include "g.h"
2 #include "f.h"
3
4 int f() {
5   return g(1);
6 }
```

```
helloworld.c
1 #include <stdio.h>
2 #include "f.h"
3
4 int main() {
5   printf( "Hi!\n" );
6   return f();
7 }
```

— 2014-04 — tools —

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Modules At Work

preprocess & compile:

- `% gcc -c g.c f.c \ helloworld.c`
- `% ls *.o`
- `f.o g.o helloworld.o`

link:

- `% gcc g.o f.o helloworld.o`

execute:

- `% ./a.out`
- Hello World.

fix and re-build:

- `% gcc -c helloworld.c`
- `% gcc g.o f.o helloworld.o`
- `% ./a.out`
- Hi!

```
g.h
1 #ifndef G_H
2 #define G_H
3
4 extern int
5   g( int x );
6 #endif

f.h
1 #ifndef F_H
2 #define F_H
3
4 extern int
5   f();
6 #endif
```

```
g.c
1 #include "g.h"
2
3 int g( int x ) {
4   return x/2;
5 }

f.c
1 #include "g.h"
2 #include "f.h"
3
4 int f() {
5   return g(1);
6 }
```

```
helloworld.c
1 #include <stdio.h>
2 #include "f.h"
3
4 int main() {
5   printf( "Hi!\n" );
6   return f();
7 }
```

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Preprocessing

helloworld.c

```
1 #include <stdio.h>
2 #include "f.h"
3
4 int main() {
5     printf( "Hello World.\n" );
6     return f();
7 }
```

- % gcc -E helloworld.c -o helloworld.i

helloworld.i

```
1 # 1 "helloworld.c"
2 # 1 "<command-line>"
3 # 1 "helloworld.c"
4 # 1 "/usr/include/stdio.h" 1 3 4
5 # 28 "/usr/include/stdio.h" 3 4
6 # 1 "/usr/include/features.h" 1 3 4
7 # 323 "/usr/include/features.h" 3 4
8 # 1 "/usr/include/x86_64-linux-gnu/bits/predefs.h" 1 3 4
9 # 324 "/usr/include/features.h" 2 3 4
10 # 356 "/usr/include/features.h" 3 4
11 # 1 "/usr/include/x86_64-linux-gnu/sys/cdefs.h" 1 3 4
12 # 359 "/usr/include/x86_64-linux-gnu/sys/cdefs.h" 3 4
13 # 1 "/usr/include/x86_64-linux-gnu/bits/wordsize.h" 1 3 4
14 # 360 "/usr/include/x86_64-linux-gnu/sys/cdefs.h" 2 3 4
15 # 357 "/usr/include/features.h" 2 3 4
16 # 388 "/usr/include/features.h" 3 4
17 # 1 "/usr/include/x86_64-linux-gnu/gnu/stubs.h" 1 3 4
18
19
20
21 # 1 "/usr/include/x86_64-linux-gnu/bits/wordsize.h" 1 3 4
22 # 5 "/usr/include/x86_64-linux-gnu/gnu/stubs.h" 2 3 4
23
24 [...]
25
26 extern int ftrylockfile (FILE *__stream) __attribute__((__nothrow__));
27
28
29 extern void funlockfile (FILE *__stream) __attribute__((__nothrow__));
30 # 936 "/usr/include/stdio.h" 3 4
31
32 # 2 "helloworld.c" 2
33 # 1 "f.h" 1
34
35
36
37 extern int
38 f();
39 # 3 "helloworld.c" 2
40
41 int main() {
42     printf( "Hello World.\n" );
43     return f();
44 }
```

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Preprocessing Directives (6.10)

```
1 #include <stdio.h>
2 #include "battery.h"
3
4 #define PI 3.1415
5
6 #define DEBUG
7 #ifdef DEBUG
8     fprintf( stderr, "honk\n" );
9 #endif
10
11 #if __GNUC__ >= 3
12 # define __pure __attribute__((pure))
13 #else
14 # define __pure /* no pure */
15 #endif
16
17 extern int f() __pure;
```

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Linking

```
provides: int g(int)
needs: ./      g.o
```

```
provides: int f()
needs: int g(int)
      f.o
```

```
provides int main()
needs:
  int f(int)
  int printf(const char*,...)
      helloworld.o
```

```
provides:
  int printf(const char*,...)
  ...
needs:
  ...
      libc.a
```

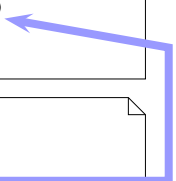
Linking

```
provides: int g(int)
needs: ./      g.o
```

```
provides: int f()
needs: int g(int)
      f.o
```

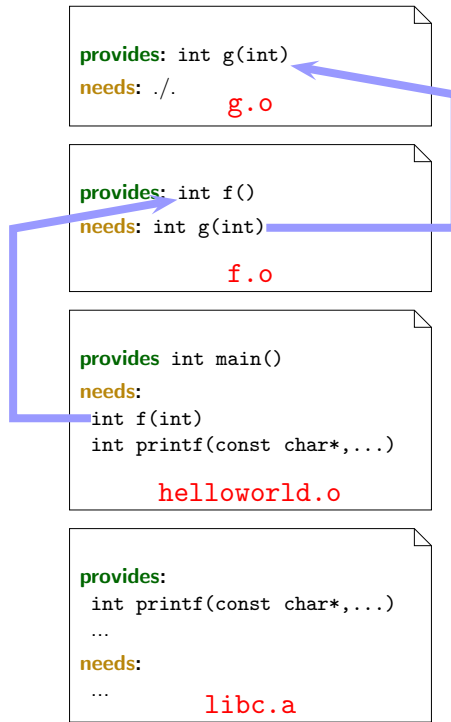
```
provides int main()
needs:
  int f(int)
  int printf(const char*,...)
      helloworld.o
```

```
provides:
  int printf(const char*,...)
  ...
needs:
  ...
      libc.a
```



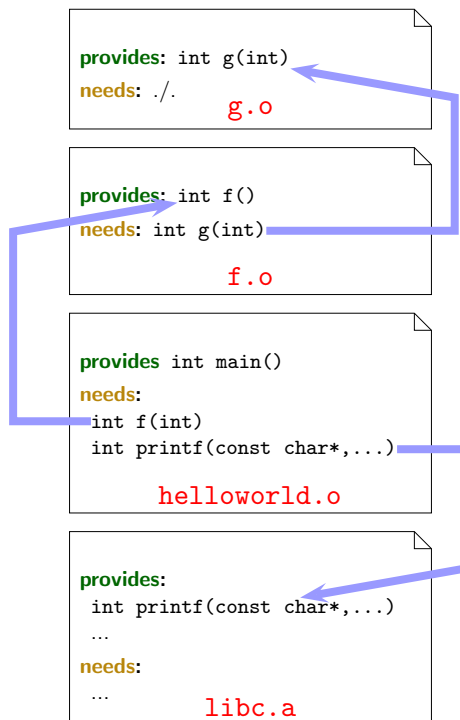
Linking

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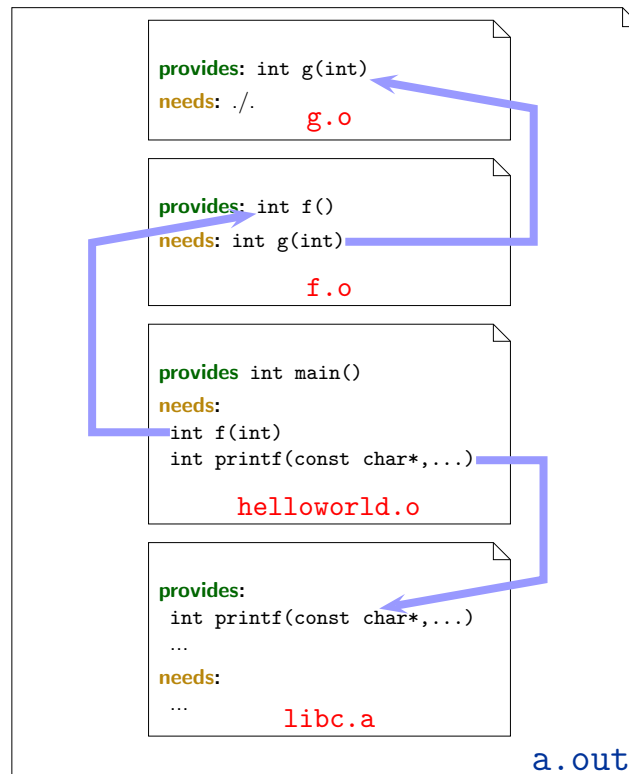


Linking

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Linking



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Compiler

`gcc [OPTION]... infile...`

`-E` — preprocess only

`-c` — compile only, don't link

Example: `gcc -c main.c` — produces `main.o`

`-o outfile` — write output to **outfile**

Example: `gcc -c -o x.o main.c` — produces `x.o`

`-g` — add debug information

`-W, -Wall, ...` — enable warnings

`-I dir` — add **dir** to **include path** for searching headers

`-L dir` — add **dir** to **library path** for searching libraries

`-D macro[=defn]` — define **macro** (to **defn**)

Example: `gcc -DDEBUG -DMAGICNUMBER=27`

`-l library` link against `liblibrary`. {a,so}, order matters

Example: `gcc a.o b.o main.o -lxy`

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→ cf. `man gcc`

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gdb(1), ddd(1), nm(1), make(1)

- **Command Line Debugger:**

```
gdb a.out [core]
```

- **GUI Debugger:**

```
ddd a.out [core]
```

(works best with debugging information compiled in (`gcc -g`))

- **Inspect Object Files:**

```
nm a.o
```

- **Build Utility:**

```
make
```

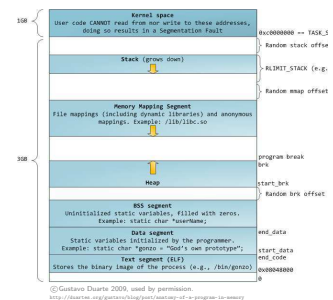
See battery controller exercise for an example.

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Core Dumps

- **Recall:** Anatomy of a Linux Program in Memory
- **Core dump:** (basically) this memory written to a file.

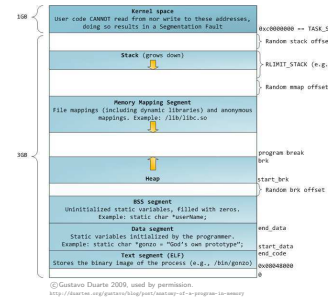


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Core Dumps

- **Recall:** Anatomy of a Linux Program in Memory
- **Core dump:** (basically) this memory written to a file.



```

1  int main() {
2      int *p;
3      *p = 27;
4      return 0;
5  }

```

— 2014-04 — — tools —

```

1 % gcc -g core.c
2 % limit coredumpsize
3 coredumpsize 0 kbytes
4 % limit coredumpsize 1g
5 % ./a.out
6 Segmentation fault (core dumped)
7 % ls -lh core
8 -rw-r--r-- 1 user user 232K Feb 29 11:11 core
9 % gdb a.out core
10 GNU gdb (GDB) 7.4.1--debian
11 [...]
12 Core was generated by './a.out'.
13 Program terminated with signal 11, Segmentation fault.
14 #0 0x000000004004b4 in main () at core.c:3
15 3*****p=27;
16 (gdb) p p
17 $1 = (int *) 0x0
18 (gdb) q

```

Formal Methods for C

Correctness and Requirements

Correctness

- Correctness is defined **with respect to** a specification.
- A program (function, ...) is **correct** (wrt. specification φ) **if and only if** it satisfies φ .
- Definition of “satisfies”: **in a minute**.

Examples:

- φ_1 : the return value is 10 divided by parameter (if parameter not 0)
- φ_2 : the value of variable x is “always” strictly greater than 3
- φ_3 : the value of i increases in each loop iteration
- ...

Common Patterns

- **State Invariants:**
 - “at **this** program point, the value of p must not be NULL”
 - “at **all** program points, the value of p must not be NULL”
(cf. **sequence points** (Annex C))
- **Data Invariants:**
 - “the value of n must be the length of s ”
- **(Function) Pre/Post Conditions:**
 - Pre-Condition: the parameter must not be 0
 - Post-Condition: the return value is 10 divided by the parameter
- **Loop Invariants:**
 - “the value of i is between 0 and array length minus 1”

*Poor Man’s Requirements Specification
aka. How to Formalize Requirements in C?*

Diagnostics (7.2)

```
1 #include <assert.h>
2 void assert( /* scalar */ expression );
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1 #include <assert.h>
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```

- “The `assert` macro puts diagnostic tests into programs; [...]

When it is executed, if `expression` (which shall have a scalar type) is false (that is, compares equal to 0), the `assert` macro

- writes information about the particular call that failed [...] on the standard error stream in an implementation-defined format.
- It then calls the `abort` function.”

Diagnostics (7.2)

```
1 #include <assert.h>
2 void assert( /* scalar */ expression );
```

- “The assert macro puts diagnostic tests into programs; [...]

When it is executed, if `expression` (which shall have a scalar type) is false (that is, compares equal to 0), the assert macro

- writes information about the particular call that failed [...] on the standard error stream in an implementation-defined format.
- It then calls the `abort` function.”

Pitfall:

- If macro `NDEBUG` is **defined** when including `<assert.h>`, `expression` **is not evaluated** (thus should be side-effect free).

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abort (7.20.4.1)

```
1 #include <stdlib.h>
2
3 void abort();
```

- “The abort function causes abnormal program termination to occur, unless [...]
- [...] An implementation-defined form of the status unsuccessful termination is returned to the host environment by means of the function call `raise(SIGABRT)`.”

(→ Core Dumps)

– 2014-04 – assert –

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Common Patterns with *assert*

- **State Invariants:**
 - “at **this** program point, the value of *p* must not be NULL”
 - “at **all** program points, the value of *p* must not be NULL” (cf. **sequence points** (Annex C))
- **Data Invariants:**
 - “the value of *n* must be the length of *s*”
- **(Function) Pre/Post Conditions:**
 - Pre-Condition: the parameter must not be 0
 - Post-Condition: the return value is 10 divided by the parameter
- **Loop Invariants:**
 - “the value of *i* is between 0 and array length minus 1”

State Invariants with *<assert.h>*

```
1 void f() {
2     int* p = (int*)malloc(sizeof(int));
3
4     if (!p)
5         return;
6
7     assert(p); // assume p is valid from here
8     // ...
9 }
10
11 void g() {
12     Node* p = find( 'a' );
13
14     assert(p); // we inserted 'a' before
15     // ...
16 }
```

Data Invariants with `<assert.h>`

```
1  typedef struct {
2      char* s;
3      int n;
4  } str;
5
6  str* construct( char* s ) {
7      str* x = (str*)malloc( sizeof(str) );
8      // ...
9      assert( (x->s == NULL && x->n == -1)
10             || (x->n == strlen( x->s ) ) );
11 }
```

Pre/Post Conditions with `<assert.h>`

```
1  int f( int x ) {
2      assert( x != 0 ); // pre-condition
3
4      int r = 10/x;
5
6      assert( r == 10/x ); // post-condition
7
8      return r;
9  }
```

Loop Invariants with `<assert.h>`

```
1 void f( int a[], int n ) {
2     int i = 0;
3
4     // holds before the loop
5     assert( 0 <= i && i <= n );
6     assert( i < 1 || a[i-1] == 0 );
7
8     while ( i < n ) {
9         // holds before each iteration
10        assert( 0 <= i && i <= n );
11        assert( i < 1 || a[i-1] == 0 );
12
13        a[i++] = 0;
14    }
15    // holds after exiting the loop
16    assert( 0 <= i && i <= n );
17    assert( i < 1 || a[i-1] == 0 );
18
19    return;
20 }
```

- 2014-04 - - assert -

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Old Variables, Ghost Variables

```
1 void xorSwap( unsigned int* a, unsigned int* b ) {
2     #ifndef NDEBUG
3         unsigned int *old_a = a, *old_b = b;
4     #endif
5     assert( a && b ); assert( a != b ); // pre-condition
6
7     *a = *a + *b;
8     *b = *a - *b;
9     *a = *a - *b;
10
11    assert( *a == *old_b && *b == *old_a ); // post-con-
12    assert( a == old_a && b == old_b );    // dition
13 }
```

- 2014-04 - - assert -

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Outlook

- Some verification tools simply verify for each assert statement:
When executed, expression is not false.
- Some verification tools support sophisticated requirements specification languages like ACSL with explicit support for
 - pre/post conditions
 - ghost variables, old values
 - data invariants
 - loop invariants
 - ...

Dependable Verification (Jackson)

Dependability

- “The program has been verified.” tells us

Dependability

- “The program has been verified.” tells us **not very much**.

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 - Platform assumptions: finite words (size?), mathematical integers, . . .
 - Environment assumptions, input values, . . .
- Assumptions are often implicit, “**in the tool**”!

Dependability

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 - Under **which assumptions** was the verification conducted?
 - Platform assumptions: finite words (size?), mathematical integers, . . .
 - Environment assumptions, input values, . . .
- Assumptions are often implicit, “**in the tool**”!
- And **what does verification mean** after all?
 - In some contexts: **testing**.
 - In some contexts: **review**.
 - In some contexts: **model-checking** procedure.
(“We verified the program!” – “What did the tool say?” – “Verification failed.”)
 - In some contexts: **model-checking tool claims correctness**.

Common Errors

Distinguish

Most **generic errors** boil down to:

- specified but **unwanted behaviour**,
e.g. under/overflows
- **initialisation issues**
e.g. automatic block scope objects
- **unspecified behaviour** (J.1)
e.g. order of evaluation in some cases
- **undefined behaviour** (J.2)
- **implementation defined behaviour** (J.3)

Conformance (4)

- “A program that is
 - correct in all other aspects,
 - operating on correct data,
 - containing **unspecified behavior**

shall be a correct program and act in accordance with 5.1.2.3. (Program Execution)

- A conforming program is one that is acceptable to a conforming implementation.
- Strictly conforming programs are intended to be maximally portable among conforming implementations.
- An implementation [of C, a compiler] shall be accompanied by a document that defines all implementation-defined and locale-specific characteristics and all extensions.

Over- and Underflows

Over- and Underflows, Casting

- Not specific to C...

```
1 void f( short a, int b ) {
2     a = b; // typing ok, but...
3 }
4
5 short a; // provisioning, implicit cast
6 if (++a < 0) { /* no */ }
7
8 if (++i > MAX.INT) {
9     /* no */ }
10
11
12 int e = 0;
13
14 void set_error() { e++; }
15 void clear_error() { e = 0; }
16
17 void g() { if (e) { /* ... */ } }
```

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Initialisation (6.7.8)

Initialisation (6.7.8)

- “If an object that has automatic storage duration is not initialized explicitly, its value is indeterminate.”

```
1 void f() {  
2     int a;  
3  
4     printf( "%i\n", a ); // surprise ...  
5 }
```

Unspecified Behaviour (J.1)

Unspecified Behaviour (J.1)

Each implementation (of a compiler) documents how the choice is made.

For example

- whether two string literals result in distinct arrays (6.4.5)
- the order in which the function designator, arguments, and subexpressions within the arguments are evaluated in a function call (6.5.2.2)
- the layout of storage for function parameters (6.9.1)
- the result of rounding when the value is out of range (7.12.9.5, ...)
- the order and contiguity of storage allocated by successive calls to `malloc` (7.20.3)
- etc. pp.

```
1 char a[] = "hello", b[] = "hello"; // a == b?
2
3 i = 0; f( ++i, ++i, ++i ); // f(1,2,3)?
4
5 int g() { int a, b; } // &a > &b ?
6
7 int* p = malloc( sizeof(int) );
8 int* q = malloc( sizeof(int) ); // q > p?
```

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Undefined Behaviour (J.2)

– 2014-04 – pitfalls –

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Undefined Behaviour (3.4.3)

“Behaviour, upon use of a non-portable or erroneous program construct or of erroneous data, for which this International Standard imposes no requirements.”

“Possible undefined behaviour ranges from

- ignoring the situation completely with **unpredictable results**,
- to behaving during **translation or program execution** in a documented manner characteristic of the environment (with or without the issuance of a diagnostic message),
- to terminating a **translation or execution** (with the issuance of a diagnostic message).”

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“An example of undefined behaviour is the behaviour on **integer overflow**.”

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Undefined Behaviour (J.2)

More examples:

- an identifier [...] contains an invalid multibyte character (5.2.1.2)

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Undefined Behaviour (J.2)

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- the value of a pointer to an object whose lifetime has ended is used (6.2.4)

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- conversion to or from an integer type produces a value outside the range that can be represented (6.3.1.4)

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- conversion between two pointer types produces a result that is incorrectly aligned (6.3.2.3)

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- the program attempts to modify a string literal (6.4.5)

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- an exceptional condition occurs during the evaluation of an expression (6.5)

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More examples:

- an identifier [...] contains an invalid multibyte character (5.2.1.2)
- an object is referred to outside of its lifetime (6.2.4)
- the value of a pointer to an object whose lifetime has ended is used (6.2.4)
- conversion to or from an integer type produces a value outside the range that can be represented (6.3.1.4)
- conversion between two pointer types produces a result that is incorrectly aligned (6.3.2.3)
- the program attempts to modify a string literal (6.4.5)
- an exceptional condition occurs during the evaluation of an expression (6.5)
- the value of the second operand of the / or % operator is zero (6.5.5)

Undefined Behaviour (J.2)

More examples:

- an identifier [...] contains an invalid multibyte character (5.2.1.2)
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- “An integer constant expression with the value 0, or such an expression cast to type `void*`, is called a **null pointer constant**. [...]”
- “The macro **NULL** is defined in `<stddef.h>` (and other headers) as a null pointer constant; see 7.17.”
- “Among the invalid values for dereferencing a pointer by the unary `*` operator are a null pointer, [...]” (6.5.3.2)

Segmentation Violation

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- **But:** other way round does not hold, accessing an object outside its lifetime does not imply a segmentation violation.
- Some platforms (e.g. SPARC): unaligned memory access, i.e. outside word boundaries, not supported by hardware (“bus error”).
Operating system notifies process, default handler: terminate, dump core.

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Locale and Common Extensions (J.4, J.5)

- J.4 Locale-specific behaviour
- J.5 Common extensions
“The following extensions are widely used in many systems, but are not portable to all implementations.”

References

[ISO, 1999] ISO (1999). Programming languages – C. Technical Report ISO/IEC 9899:1999, ISO. Second edition, 1999-12-01.