Formal Methods for C

Seminar – Summer Semester 2014

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Plan

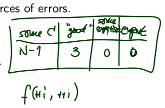
- (**15 min.**) Topic lottery: prepare lottery ticket with
  - name
  - first preference topic
  - second preference topic
- Introduction to C (1)
- (**15 min.**) The VM (Marius)

Overview

Goals

Educational Objectives: Capabilities for following tasks/questions.

- Rough overview over concepts of the C programming language.
  - IOW: know, what to look for in books/manuals.
    (We try to stick with the names from of ISO/IEC 9899:1999.)
  - IOW: don't be badly surprised from the examples.
- The concept of pointers.
- Basic work-flow, tool-usage (headers, sources, compiler, linker).
- Orthogonal: Rough overview over common sources of errors.
- Formal methods and C.
- **Not**: reference manual, each and every feature.
- **Not**: programming course.



Everybody Say "Hello" to C

```
#include <stdio.h>

int g( int x ) {
  return x/2;
}

int f() {
  return g(1);
}

int main() {
  printf( "Hello World.\n" );
  return f();
}
```


42 Years of C

1972: Created by **Dennis Ritchie** († 2011) for Unix system programming.
1978: Brian W. Kernighan & Dennis Ritchie:
"The C Programming Language" – "K&R C",
1989: ANSI X3.159-1989 – C89, **C90** (still most widely used (?))
1999: ISO/IEC 9899:1999 – C99, (use --std=c99 for gcc(1))
2011: ISO/IEC 9899:2011 – C11

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- Compilers for virtually every platform (CPU + operating system) available. Virtually every CPU vendor offers an own C compiler, in particular in the embedded domain (MSP 430, ARM, intel...).
- Still No. 1 programming language for embedded systems software, hardware drivers, performance critical applications, ...
- Preferred by many embedded programmers for "lack of surprises": (without optimisation) direct correspondence between C code and assembler.
- Resources widely controllable by programmer, downside: programmer needs to "know what one's doing"

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

Comments

Comments (6.5.9)

- one line comment, until end of line: `// ...`
- generic comment, no nesting: `/* ... */`
- corner cases:

```
"a//b"                    // four-character string literal
#include "//e"            // undefined behavior
// */                     // comment, not syntax error
f = g/**//h;              // equivalent to f = g / h;
//\
i();                      // part of a two-line comment
/\
/ j();                    // part of a two-line comment
#define glue(x,y) x##y
glue(/,/) k();            // syntax error, not comment
/*//*/ l();               // equivalent to l();
m = n//**/o
    + p;                  // equivalent to m = n + p;
```


Declarations and Scopes

Variables

Basic Types (6.2.5), Constants (6.4.4)

```c
char c = 'a', d = 93;

int x = 027; // octal!
long int y = 3L, z;
short int w = 0xBEEF;
```

"[...] **char** is large enough to store any member of the basic exec. character set."

"A 'plain' **int** object has the natural size suggested by the architecture of the execution environment (large enough [for values] **INT_MIN** to **INT_MAX**)."

```c
unsigned int x = 27U;
```

char, **short int**, **int**, **long int**, **long long int** also as **unsigned**.

```c
float f = 1;
double g = 314159e−5;
long double h;
```


Bool (6.2.5)

- Only introduced in C99.
- "An object declared as type **_Bool** is large enough to store the values 0 and 1."
- **<stdbool.h>** (→ later) defines **bool**, **true**, **false** as macros (→ later).
- Before C99, and **still very common**:
  - Use scalar type (including pointers).
  - **0**: **false**
  - **everything else**: **true**
  - values of boolean expressions: 0, 1

```c
int y = 27;
int x = 13 && (y > 0); // value of x becomes 1
```


Derived Types (6.2.5), (6.7)

- **array types**:

```c
int a[10];
char b[2][3];
```

- **structured types**:

```c
typedef struct {
  int n;
  double d;
} S; // declaration of type 'S'

S x; // declaration of variable 'x' of type 'S'

struct { int a; double b; } y; // declaration of...?
typedef struct { S[3] c; double d; } T;
```

Note: x and y are of different type!

- **union types**: not here
- **function types**, **pointer types**: later

Declaration Syntax

- ...takes a little bit getting used to:

```c
int c, *p, a[3], *q[2], (*f)(int);
```

- is a shorthand notation for:

```c
int  c;         // integer
int *p;         // pointer to integer
int  a[3];      // array of 3 integers
int *q[2];      // array of 2 pointers to integer
int (*f)(int);  // function pointer...
```

- And what's declared here, what is its type?

```c
int (*g)( int (*)(int*[2]) ); // ...?
```


Expressions

Expressions (6.5)

- "An **expression** is a sequence of operators and operands that specifies computation of a value, or that designates an object or a function, or that generates side effects, or that performs a combination thereof."
- basically like Java:
  - postfix operators: `a++, p.x, q->y`
  - unary operators: `++a, sizeof(int), &a, *p`
  - cast operators: `(double)a`
  - multiplicative, additive
  - relational, equality: `a < b, a == b, a != b`
  - logical operators: `(a < b) && (c > 0)`
  - conditional operator: `a < b ? a : b`
  - assignment operator (are expressions!): `a = b, a += b, a = b = 0`
  - comma operator: `a = b, c = d`

Boolean Logic (6.3.2.1, 6.5.13–6.5.15)

- "When any scalar value is converted to `_Bool`, the result is 0 [**false**] if the value compares equal to 0; otherwise, the result is 1." (6.3.2.1)
- `a != 0` and 'a' are equivalent (if a is of scalar type), so are `a == 0` and `!a`
- for pointers (later): `p == NULL` and `!p` are equivalent

Bitwise Operators (6.5.3.3, 6.5.7, 6.5.10–12)

- Often used in hardware level programming: Communicate with "the hardware" via memory-mapped registers – single bits or groups of bits have particular, platform dependent meaning.
- Bitwise And, Or, Xor (6.5.10-12): 0101_2 `&` 1100_2 `==` $????_2$ bitwise 0100_2
  0101_2 `&&` 1100_2 `==` $????_2$ 0001_2
- Useful idioms (assuming 4-bit type):
  - Set the 3rd bit: `a |=` 0100_2
  - Clear the 2nd bit: `a &=` 1101_2
  - Test whether 2nd bit set: `a &` 0010_2
- Shift (6.5.7): `a << 2`, `a >> 2` (unsigned (!) filled up with 0 at left and right)
- Bitwise complement (6.5.3.3): `~a`

Be careful with signed types (bit-operations at best on unsigned):
`~(int(1)) == 0xFFFFFFFE // == -2`

Lvalues (6.3.2.1)

```
int x, a[3], *p;

x = 27;
a[1] = 0;
p = &x;
*p = 13;

&x = ...; // no
a = ...; // no, only as initializer
```

- "An **lvalue** is an expression with an object type or an incomplete type other than void;"
- "The name "lvalue" [comes from] `E1 = E2`, in which the **left** operand E1 is required to be a (modifiable) lvalue.
  What is sometimes called "rvalue" is in this International Standard described as the "value of an expression".
  An obvious example of an lvalue is an identifier of an object."

Statements

Statements (6.8)

- "A **statement** specifies an action to be performed. Except as indicated, statements are executed in sequence."
- also basically like Java:
  - Selection statements (6.8.4): `if`, `else`, `switch`
  - Iteration statements (6.8.5): `while`, `do ... while`, `for`
  - Jump statements (6.8.6): `goto`, `continue`, `break`, `return`

Functions

Function Definitions (6.9.1)

```
int max( int a, int b )
{
  return a > b ? a : b;
}
```

- no nesting, no member functions
- all in file (global) scope (but: module scope possible (**later**))
- call-by-value semantics (call-by-reference: **later**)

Function declaration (vs. **definition**):

```
int max( int a, int b ); // param. names just "decoration"
int max( int , int );
```

- "Zero or many declarations, exactly one definition."

Scopes

Scopes of Identifiers (6.2.1)

```
int a; // file scope (F)

struct { int a; } s; // name-space

int f( int a ) // block scope, block (A)
{ /* <-------------------------- (A) */
  if (a) { /* <----------------- (B) */
    a = 0; // uses a:(A)

    int a = 27; // block scope, block (B)

    s.a = a; // uses a:(B)
  }
  return a; // uses a:(A)
}

int main() { return f(a); /* uses a:(F) */ }
```

- "The same identifier can denote different entities at diff. points in the program."
- "For each different entity that an identifier designates, the identifier is **visible** (i.e., can be used) only within a region of program text called its **scope**."

Scopes of Identifiers (6.2.1)

- "**Different entities** designated by the **same identifier** either have different scopes, or are in different name spaces. **There are four kinds of scopes**: function, file, block, and function prototype."
- "A label name is the only kind of identifier that has function scope."
- "Every other identifier has scope determined by the placement of its declaration (in a declarator or type specifier)."
- **Declare before use**: each identifier must be declared before (i.e. earlier in the source file) its first use in, e.g., an expression. (**Unlike Java!**)

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- **Declare before use**: each identifier must be declared before (i.e. earlier in the source file) its first use in, e.g., an expression. (**Unlike Java!**)
- **"Hidden" identifiers are not accessible**:

```
int a; /* (F) */

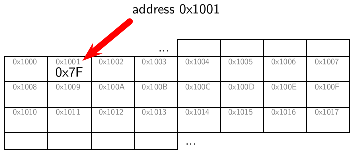
void f( int a ) { /* (A) */
  a = 0; // uses a:(A),
         // a:(F) not acccessible here, "hidden" by a:(A)
}
```


Pointers

Variables in the System's Memory

```
char c = 127;
```

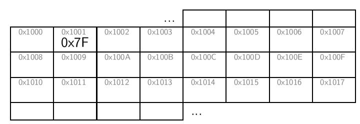
the compiler chose to store values of **'c'** at memory cell with address 0x1001



Assigning Variables = Update Memory

```
char c = 127;
c = c + 1;
```

"$c = c + 1$" means: the new value of c is the old value plus 1; in assembler:
`read 0x1001,`R`; inc `R`;`
`write `R`,0x1001`



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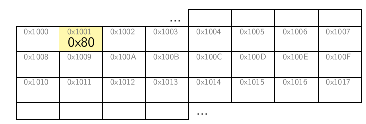
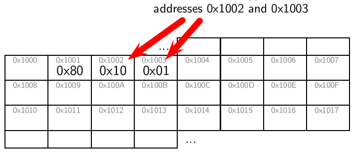


A Pointer to 'c' (16-bit Architecture)

```
char c = 127;
c = c + 1;
char* p = &c;
```

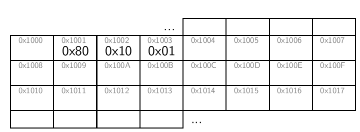
the compiler chose to store values of variable **'p'** at memory cells (!) with addresses 0x1002 and 0x1003



Dereferencing Pointers

```
char c = 127;
c = c + 1;
char* p = &c;
*p = *p + 3;
```

dereference



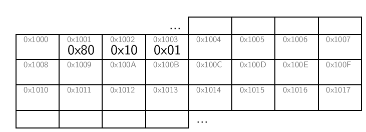
Dereferencing Pointers

```
char c = 127;
c = c + 1;
char* p = &c;
*p = *p + 3;
```

***p, rhs**: get the value of p (0x1001) and read the value **at that address** (at 0x1001, yields 0x80)

***p, lhs**: get the value of p again (0x1001), write the addition result (0x83) **to that address** (to 0x1001)

add 3 to the value just obtained (yields 0x83)



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add 3 to the value just obtained (yields 0x83)

0x1000	0x1001	0x1002	0x1003	0x1004	0x1005	0x1006	0x1007
	0x83	0x10	0x01				
0x1008	0x1009	0x100A	0x100B	0x100C	0x100D	0x100E	0x100F
0x1010	0x1011	0x1012	0x1013	0x1014	0x1015	0x1016	0x1017

...

Assigning Pointers

```
char c = 127;
c = c + 1;
char* p = &c;
*p = *p + 3;
char* q = p;
```

assume the compiler choses to store values of variable **'q'** at memory cells (!) with addresses 0x1004 and 0x1005

0x1000	0x1001	0x1002	0x1003	0x1004	0x1005	0x1006	0x1007
	0x80	0x10	0x01	??	??		
0x1008	0x1009	0x100A	0x100B	0x100C	0x100D	0x100E	0x100F
0x1010	0x1011	0x1012	0x1013	0x1014	0x1015	0x1016	0x1017

...

Assigning Pointers

```
char c = 127;
c = c + 1;
char* p = &c;
*p = *p + 3;
char* q = p;
```

p = *p +3;
0x83
0x86
↳ 0x1002 0x00 0x1003 0x86
*p = 0;

0x1000	0x1001	0x1002	0x1003	0x1004	0x1005	0x1006	0x1007
	0x83	0x10	0x01	0x10	0x01		
0x1008	0x1009	0x100A	0x100B	0x100C	0x100D	0x100E	0x100F
0x1010	0x1011	0x1012	0x1013	0x1014	0x1015	0x1016	0x1017

...

Pointers to Pointers

```
char c = 127;
c = c + 1;
char* p = &c;
*p = *p + 3;
char* q = p;
char** r = &q;
```

assume the compiler choses to store values of variable **'r'** at memory cells (!) with addresses 0x1006 and 0x1007

0x1000	0x1001	0x1002	0x1003	0x1004	0x1005	0x1006	0x1007
	0x80	0x10	0x01	0x10	0x01	??	??
0x1008	0x1009	0x100A	0x100B	0x100C	0x100D	0x100E	0x100F
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```

0x1000	0x1001	0x1002	0x1003	0x1004	0x1005	0x1006	0x1007
	0x83	0x10	0x01	0x10	0x01	0x10	0x04
0x1008	0x1009	0x100A	0x100B	0x100C	0x100D	0x100E	0x100F
0x1010	0x1011	0x1012	0x1013	0x1014	0x1015	0x1016	0x1017

...

Using Pointers to Pointers

```
char c = 127;
c = c + 1;
char* p = &c;
*p = *p + 3;
char* q = p;
char** r = &q;
*r = p;
**r = 5;
```

0x1000	0x1001	0x1002	0x1003	0x1004	0x1005	0x1006	0x1007
	0x83	0x10	0x01	0x10	0x01	0x10	0x04
0x1008	0x1009	0x100A	0x100B	0x100C	0x100D	0x100E	0x100F
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Using Pointers to Pointers

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char c = 127;
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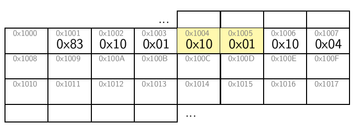

Using Pointers to Pointers

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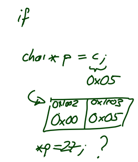

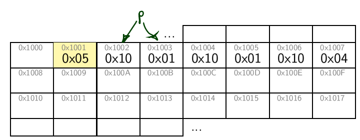

Pointers vs. Arrays

Arrays

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


Arrays

reserve some space for 5 **char**s...

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

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

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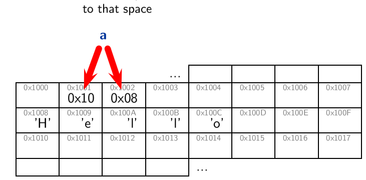
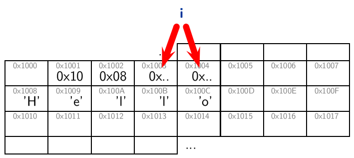


Arrays

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



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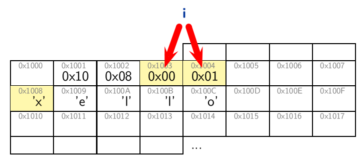

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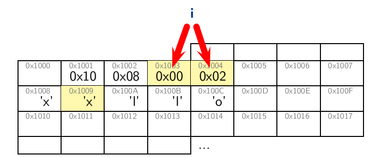

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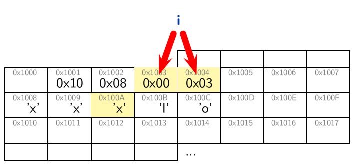

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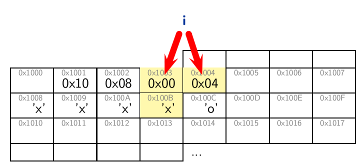

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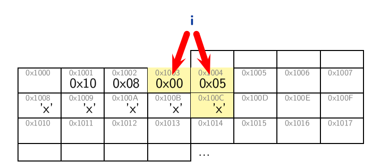

Arrays vs. Pointers

```
char a[5] = { 'H', 'e', 'l', 'l', 'o' };
char* p = a; // not &a !
for (int i = 0; i < 5; ++i, ++p)
  *p = 'o';
```

p → 0x1003, 0x1004

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

...

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  *p = 'o';
```

p → 0x1003, 0x1004

0x1000	0x1001 0x10	0x1002 0x08	0x1003 0x10	0x1004 0x08	0x1005	0x1006	0x1007
0x1008 'x'	0x1009 'x'	0x100A 'x'	0x100B 'x'	0x100C 'x'	0x100D	0x100E	0x100F
0x1010	0x1011	0x1012	0x1013	0x1014	0x1015	0x1016	0x1017

...

Arrays vs. Pointers

```
char a[5] = { 'H', 'e', 'l', 'l', 'o' };
char* p = a; // not &a !
for (int i = 0; i < 5; ++i, ++p)
  *p = 'o';
```

p → 0x1003, 0x1004

0x1000	0x1001 0x10	0x1002 0x08	0x1003 0x10	0x1004 0x09	0x1005	0x1006	0x1007
0x1008 'o'	0x1009 'x'	0x100A 'x'	0x100B 'x'	0x100C 'x'	0x100D	0x100E	0x100F
0x1010	0x1011	0x1012	0x1013	0x1014	0x1015	0x1016	0x1017

...

Arrays vs. Pointers

```
char a[5] = { 'H', 'e', 'l', 'l', 'o' };
char* p = a; // not &a !
for (int i = 0; i < 5; ++i, ++p)
  *p = 'o';
```

p → 0x1003, 0x1004

0x1000	0x1001 0x10	0x1002 0x08	0x1003 0x10	0x1004 0x0A	0x1005	0x1006	0x1007
0x1008 'o'	0x1009 'o'	0x100A 'x'	0x100B 'x'	0x100C 'x'	0x100D	0x100E	0x100F
0x1010	0x1011	0x1012	0x1013	0x1014	0x1015	0x1016	0x1017

...

Arrays vs. Pointers

```
char a[5] = { 'H', 'e', 'l', 'l', 'o' };
char* p = a; // not &a !
for (int i = 0; i < 5; ++i, ++p)
  *p = 'o';
```

p → 0x1003, 0x1004

0x1000	0x1001 0x10	0x1002 0x08	0x1003 0x10	0x1004 0x0B	0x1005	0x1006	0x1007
0x1008 'o'	0x1009 'o'	0x100A 'o'	0x100B 'x'	0x100C 'x'	0x100D	0x100E	0x100F
0x1010	0x1011	0x1012	0x1013	0x1014	0x1015	0x1016	0x1017

...

Arrays vs. Pointers

```
char a[5] = { 'H', 'e', 'l', 'l', 'o' };
char* p = a; // not &a !
for (int i = 0; i < 5; ++i, ++p)
  *p = 'o';
```

p → 0x1003, 0x1004

0x1000	0x1001 0x10	0x1002 0x08	0x1003 0x10	0x1004 0x0C	0x1005	0x1006	0x1007
0x1008 'o'	0x1009 'o'	0x100A 'o'	0x100B 'o'	0x100C 'x'	0x100D	0x100E	0x100F
0x1010	0x1011	0x1012	0x1013	0x1014	0x1015	0x1016	0x1017

...

Arrays vs. Pointers

```c
char a[5] = { 'H', 'e', 'l', 'l', 'o' };
char* p = a; // not &a !
for (int i = 0; i < 5; ++i, ++p)
  *p = 'o';
```

p

0x1000	0x1001 0x10	0x1002 0x08	0x1003 0x10	0x1004 0x0D	0x1005	0x1006	0x1007
0x1008 'o'	0x1009 'o'	0x100A 'o'	0x100B 'o'	0x100C 'o'	0x100D	0x100E	0x100F
0x1010	0x1011	0x1012	0x1013	0x1014	0x1015	0x1016	0x1017

…

Integer Arrays

reserve some space for 3 **int**s…

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

…and let **a** point to that space

a

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

…

Integer Arrays

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

i

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

…

Integer Arrays

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

i

0x1000	0x1001 0x10	0x1002 0x08	0x1003 0x00	0x1004 0x01	0x1005	0x1006	0x1007
0x1008 0x00	0x1009 0x27	0x100A 0x00	0x100B 0x08	0x100C 0x12	0x100D 0x34	0x100E	0x100F
0x1010	0x1011	0x1012	0x1013	0x1014	0x1015	0x1016	0x1017

…

Integer Arrays

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

i

0x1000	0x1001 0x10	0x1002 0x08	0x1003 0x00	0x1004 0x02	0x1005	0x1006	0x1007
0x1008 0x00	0x1009 0x27	0x100A 0x00	0x100B 0x27	0x100C 0x12	0x100D 0x34	0x100E	0x100F
0x1010	0x1011	0x1012	0x1013	0x1014	0x1015	0x1016	0x1017

…

Integer Arrays

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

i

0x1000	0x1001 0x10	0x1002 0x08	0x1003 0x00	0x1004 0x03	0x1005	0x1006	0x1007
0x1008 0x00	0x1009 0x27	0x100A 0x00	0x100B 0x27	0x100C 0x00	0x100D 0x27	0x100E	0x100F
0x1010	0x1011	0x1012	0x1013	0x1014	0x1015	0x1016	0x1017

…

Integer Arrays vs. Pointers

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

p

0x1000	0x1001 0x10	0x1002 0x08	0x1003 0x..	0x1004 0x..	0x1005	0x1006	0x1007
0x1008 0x00	0x1009 0x27	0x100A 0x00	0x100B 0x27	0x100C 0x00	0x100D 0x27	0x100E	0x100F
0x1010	0x1011	0x1012	0x1013	0x1014	0x1015	0x1016	0x1017

...

Integer Arrays vs. Pointers

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

p

0x1000	0x1001 0x10	0x1002 0x08	0x1003 0x10	0x1004 0x08	0x1005	0x1006	0x1007
0x1008 0x00	0x1009 0x27	0x100A 0x00	0x100B 0x27	0x100C 0x00	0x100D 0x27	0x100E	0x100F
0x1010	0x1011	0x1012	0x1013	0x1014	0x1015	0x1016	0x1017

...

Integer Arrays vs. Pointers

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

p

0x1000	0x1001 0x10	0x1002 0x08	0x1003 0x10	0x1004 0x0A	0x1005	0x1006	0x1007
0x1008 0x34	0x1009 0x21	0x100A 0x00	0x100B 0x27	0x100C 0x00	0x100D 0x27	0x100E	0x100F
0x1010	0x1011	0x1012	0x1013	0x1014	0x1015	0x1016	0x1017

...

Integer Arrays vs. Pointers

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

p

0x1000	0x1001 0x10	0x1002 0x08	0x1003 0x10	0x1004 0x0C	0x1005	0x1006	0x1007
0x1008 0x34	0x1009 0x21	0x100A 0x34	0x100B 0x21	0x100C 0x00	0x100D 0x27	0x100E	0x100F
0x1010	0x1011	0x1012	0x1013	0x1014	0x1015	0x1016	0x1017

...

Integer Arrays vs. Pointers

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

p

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

...

Pointers to 'void', Pointer Arithmetic

Pointer to 'void'

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

p q

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

...

Pointer to 'void'

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

p q

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

...

Pointer to 'void'

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

p q

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

...

Pointer to 'void'

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

p q

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

...

Pointer to 'void'

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

p q

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

...

Pointer to 'void'

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

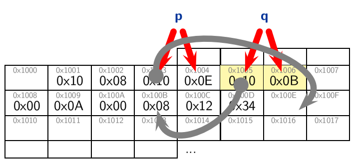
p q

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

...

Pointer to 'void'

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



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.

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


Pointer Arithmetic

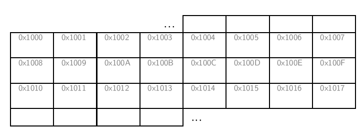
```
int[3] a = { 10, 010, 0x1234 }, i = 0;

int* p = a; // not &a !

if (a[0] == *p) i++;
if (a[1] == *(p+1)) i++;
if (a[2] == *(p+2)) i++;

if (&(a[2]) - p == 2) i++;

void* q = a;

if (a[2] == *((int*)(q + (2 * sizeof(int))))) i++;

// i == 5
```

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

Pointers for Call By Reference

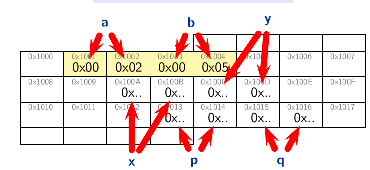
Call By Reference with Pointers

```
void f( int x, int y ) {
  x++, y++;
}
void g( int* p, int* q ) {
  (*p)++, (*q)++;
}
int a = 2, b = 5;
f( a, b );
g( &a, &b );
```



Call By Reference with Pointers

```
void f( int x, int y ) {
  x++, y++;
}
void g( int* p, int* q ) {
  (*p)++, (*q)++;
}
int a = 2, b = 5;
f( a, b );
g( &a, &b );
```



Call By Reference with Pointers

```
void f( int x, int y ) {
  x++, y++;
}
void g( int* p, int* q ) {
  (*p)++, (*q)++;
}
int a = 2, b = 5;
f( a, b );
g( &a, &b );
```

...

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

...

Call By Reference with Pointers

```
void f( int x, int y ) {
  x++, y++;
}
void g( int* p, int* q ) {
  (*p)++, (*q)++;
}
int a = 2, b = 5;
f( a, b );
g( &a, &b );
```

...

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

...

Call By Reference with Pointers

```
void f( int x, int y ) {
  x++, y++;
}
void g( int* p, int* q ) {
  (*p)++, (*q)++;
}
int a = 2, b = 5;
f( a, b );
g( &a, &b );
```

...

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

...

Call By Reference with Pointers

```
void f( int x, int y ) {
  x++, y++;
}
void g( int* p, int* q ) {
  (*p)++, (*q)++;
}
int a = 2, b = 5;
f( a, b );
g( &a, &b );
```

...

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

...

Call By Reference with Pointers

```
void f( int x, int y ) {
  x++, y++;
}
void g( int* p, int* q ) {
  (*p)++, (*q)++;
}
int a = 2, b = 5;
f( a, b );
g( &a, &b );
```

...

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

...

Call By Reference with Pointers

```
void f( int x, int y ) {
  x++, y++;
}
void g( int* p, int* q ) {
  (*p)++, (*q)++;
}
int a = 2, b = 5;
f( a, b );
g( &a, &b );
```

...

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

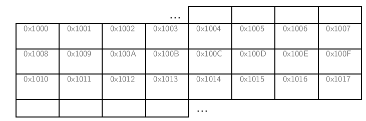
...

Dynamic Storage & Storage Duration

Dynamic Storage Allocation

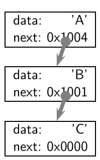
A Linked List

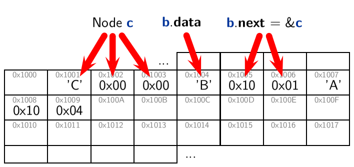
```c
typedef struct Node {
  char data;
  struct Node* next;
} Node;

Node c = { 'C', 0 };
Node b = { 'B', &c };
Node a = { 'A', &b };
```



A Linked List

```c
typedef struct Node {
  char data;
  struct Node* next;
} Node;

Node c = { 'C', 0 };
Node b = { 'B', &c };
Node a = { 'A', &b };
```

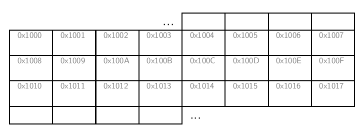




Dynamic Storage Allocation

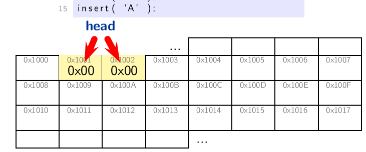
```c
typedef struct Node {
  char data; struct Node* next; } Node;

Node *head = 0, *hlp;

void insert( char d ) {
  hlp = (Node*)malloc( sizeof(Node) );
  hlp->data = d;
  hlp->next = head;
  head = hlp;
}

insert( 'C' );
insert( 'B' );
insert( 'A' );
```

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



Dynamic Storage Allocation

```c
typedef struct Node {
  char data; struct Node* next; } Node;

Node *head = 0, *hlp;

void insert( char d ) {
  hlp = (Node*)malloc( sizeof(Node) );
  hlp->data = d;
  hlp->next = head;
  head = hlp;
}

insert( 'C' );
insert( 'B' );
insert( 'A' );
```



Dynamic Storage Allocation

```
typedef struct Node {
  char data; struct Node* next; } Node;

Node *head = 0, *hlp;

void insert( char d ) {
  hlp = (Node*)malloc( sizeof(Node) );
  hlp->data = d;
  hlp->next = head;
  head = hlp;
}

insert( 'C' );
insert( 'B' );
insert( 'A' );
```

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

...

Dynamic Storage Allocation

```
typedef struct Node {
  char data; struct Node* next; } Node;

Node *head = 0, *hlp;

void insert( char d ) {
  hlp = (Node*)malloc( sizeof(Node) );
  hlp->data = d;
  hlp->next = head;
  head = hlp;
}

insert( 'C' );
insert( 'B' );
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..		

...

Dynamic Storage Allocation

```
typedef struct Node {
  char data; struct Node* next; } Node;

Node *head = 0, *hlp;

void insert( char d ) {
  hlp = (Node*)malloc( sizeof(Node) );
  hlp->data = d;
  hlp->next = head;
  head = hlp;
}

insert( 'C' );
insert( 'B' );
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..		

...

Dynamic Storage Allocation

```
typedef struct Node {
  char data; struct Node* next; } Node;

Node *head = 0, *hlp;

void insert( char d ) {
  hlp = (Node*)malloc( sizeof(Node) );
  hlp->data = d;
  hlp->next = head;
  head = hlp;
}

insert( 'C' );
insert( 'B' );
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		

...

Dynamic Storage Allocation

```
typedef struct Node {
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Node *head = 0, *hlp;

void insert( char d ) {
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}

insert( 'C' );
insert( 'B' );
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		

...

Dynamic Storage Allocation

```
typedef struct Node {
  char data; struct Node* next; } Node;

Node *head = 0, *hlp;

void insert( char d ) {
  hlp = (Node*)malloc( sizeof(Node) );
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  hlp->next = head;
  head = hlp;
}

insert( 'C' );
insert( 'B' );
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
			'C'	0x00	0x00		

...

Dynamic Storage Allocation

```c
typedef struct Node {
  char data; struct Node* next; } Node;

Node *head = 0, *hlp;

void insert( char d ) {   // ➜
  hlp = (Node*)malloc( sizeof(Node) );
  hlp->data = d;
  hlp->next = head;
  head = hlp;
}

insert( 'C' );
insert( 'B' );
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
			'C'	0x00	0x00		

Dynamic Storage Allocation

```c
typedef struct Node {
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Node *head = 0, *hlp;

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  hlp->next = head;
  head = hlp;
}

insert( 'C' );
insert( 'B' );
insert( 'A' );
```

data: 'C'
next: 0x0000

0x1000	0x1001	0x1002	0x1003	0x1004	0x1005	0x1006	0x1007
	0x10	0x13	0x10	0x08			
0x1008	0x1009	0x100A	0x100B	0x100C	0x100D	0x100E	0x100F
'..'	0x..	0x..					
0x1010	0x1011	0x1012	0x1013	0x1014	0x1015	0x1016	0x1017
			'C'	0x00	0x00		

Dynamic Storage Allocation

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  head = hlp;
}

insert( 'C' );
insert( 'B' );
insert( 'A' );
```

data: 'C'
next: 0x0000

0x1000	0x1001	0x1002	0x1003	0x1004	0x1005	0x1006	0x1007
	0x10	0x13	0x10	0x08			
0x1008	0x1009	0x100A	0x100B	0x100C	0x100D	0x100E	0x100F
'B'	0x..	0x..					
0x1010	0x1011	0x1012	0x1013	0x1014	0x1015	0x1016	0x1017
			'C'	0x00	0x00		

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  head = hlp;
}

insert( 'C' );
insert( 'B' );
insert( 'A' );
```

data: 'C'
next: 0x0000

0x1000	0x1001	0x1002	0x1003	0x1004	0x1005	0x1006	0x1007
	0x10	0x13	0x10	0x08			
0x1008	0x1009	0x100A	0x100B	0x100C	0x100D	0x100E	0x100F
'B'	0x10	0x13					
0x1010	0x1011	0x1012	0x1013	0x1014	0x1015	0x1016	0x1017
			'C'	0x00	0x00		

Dynamic Storage Allocation

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  head = hlp;   // ➜
}

insert( 'C' );
insert( 'B' );
insert( 'A' );
```

data: 'C'
next: 0x0000

0x1000	0x1001	0x1002	0x1003	0x1004	0x1005	0x1006	0x1007
	0x10	0x08	0x10	0x08			
0x1008	0x1009	0x100A	0x100B	0x100C	0x100D	0x100E	0x100F
'B'	0x10	0x13					
0x1010	0x1011	0x1012	0x1013	0x1014	0x1015	0x1016	0x1017
			'C'	0x00	0x00		

Dynamic Storage Allocation

```c
typedef struct Node {
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void insert( char d ) {
  hlp = (Node*)malloc( sizeof(Node) );
  hlp->data = d;
  hlp->next = head;
  head = hlp;
}

insert( 'C' );
insert( 'B' );
insert( 'A' );   // ➜
```

data: 'B'
next: 0x1013

data: 'C'
next: 0x0000

0x1000	0x1001	0x1002	0x1003	0x1004	0x1005	0x1006	0x1007
	0x10	0x08	0x10	0x08			
0x1008	0x1009	0x100A	0x100B	0x100C	0x100D	0x100E	0x100F
'B'	0x10	0x13					
0x1010	0x1011	0x1012	0x1013	0x1014	0x1015	0x1016	0x1017
			'C'	0x00	0x00		

Dynamic Storage Allocation

```c
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  hlp = (Node*)malloc( sizeof(Node) );
  hlp->data = d;
  hlp->next = head;
  head = hlp;
}

insert( 'C' );
insert( 'B' );
insert( 'A' );
```

data: 'B'
next: 0x1013

data: 'C'
next: 0x0000

0x1000	0x1001 0x10	0x1002 0x08	0x1003 0x10	0x1004 0x08	0x1005	0x1006	0x1007
0x1008 'B'	0x1009 0x10	0x100A 0x13	0x100B	0x100C	0x100D	0x100E	0x100F
0x1010	0x1011	0x1012	0x1013 'C'	0x1014 0x00	0x1015 0x00	0x1016	0x1017

…

Dynamic Storage Allocation

```c
typedef struct Node {
  char data; struct Node* next; } Node;

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void insert( char d ) {
  hlp = (Node*)malloc( sizeof(Node) );
  hlp->data = d;
  hlp->next = head;
  head = hlp;
}

insert( 'C' );
insert( 'B' );
insert( 'A' );
```

data: 'B'
next: 0x1013

data: 'C'
next: 0x0000

0x1000	0x1001 0x10	0x1002 0x08	0x1003 0x10	0x1004 0x0D	0x1005	0x1006	0x1007
0x1008 'B'	0x1009 0x10	0x100A 0x13	0x100B	0x100C	0x100D '..'	0x100E 0x..	0x100F 0x..
0x1010	0x1011	0x1012	0x1013 'C'	0x1014 0x00	0x1015 0x00	0x1016	0x1017

…

Dynamic Storage Allocation

```c
typedef struct Node {
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void insert( char d ) {
  hlp = (Node*)malloc( sizeof(Node) );
  hlp->data = d;
  hlp->next = head;
  head = hlp;
}

insert( 'C' );
insert( 'B' );
insert( 'A' );
```

data: 'B'
next: 0x1013

data: 'C'
next: 0x0000

0x1000	0x1001 0x10	0x1002 0x08	0x1003 0x10	0x1004 0x0D	0x1005	0x1006	0x1007
0x1008 'B'	0x1009 0x10	0x100A 0x13	0x100B	0x100C	0x100D 'A'	0x100E 0x..	0x100F 0x..
0x1010	0x1011	0x1012	0x1013 'C'	0x1014 0x00	0x1015 0x00	0x1016	0x1017

…

Dynamic Storage Allocation

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  hlp = (Node*)malloc( sizeof(Node) );
  hlp->data = d;
  hlp->next = head;
  head = hlp;
}

insert( 'C' );
insert( 'B' );
insert( 'A' );
```

data: 'B'
next: 0x1013

data: 'C'
next: 0x0000

0x1000	0x1001 0x10	0x1002 0x08	0x1003 0x10	0x1004 0x0D	0x1005	0x1006	0x1007
0x1008 'B'	0x1009 0x10	0x100A 0x13	0x100B	0x100C	0x100D 'A'	0x100E 0x10	0x100F 0x08
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…

Dynamic Storage Allocation

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  hlp->data = d;
  hlp->next = head;
  head = hlp;
}

insert( 'C' );
insert( 'B' );
insert( 'A' );
```

data: 'B'
next: 0x1013

data: 'C'
next: 0x0000

0x1000	0x1001 0x10	0x1002 0x0D	0x1003 0x10	0x1004 0x0D	0x1005	0x1006	0x1007
0x1008 'B'	0x1009 0x10	0x100A 0x13	0x100B	0x100C	0x100D 'A'	0x100E 0x10	0x100F 0x08
0x1010	0x1011	0x1012	0x1013 'C'	0x1014 0x00	0x1015 0x00	0x1016	0x1017

…

Dynamic Storage Allocation

```c
typedef struct Node {
  char data; struct Node* next; } Node;

Node *head = 0, *hlp;

void insert( char d ) {
  hlp = (Node*)malloc( sizeof(Node) );
  hlp->data = d;
  hlp->next = head;
  head = hlp;
}

insert( 'C' );
insert( 'B' );
insert( 'A' );
```

data: 'A'
next: 0x1008

data: 'B'
next: 0x1013

data: 'C'
next: 0x0000

0x1000	0x1001 0x10	0x1002 0x0D	0x1003 0x10	0x1004 0x0D	0x1005	0x1006	0x1007
0x1008 'B'	0x1009 0x10	0x100A 0x13	0x100B	0x100C	0x100D 'A'	0x100E 0x10	0x100F 0x08
0x1010	0x1011	0x1012	0x1013 'C'	0x1014 0x00	0x1015 0x00	0x1016	0x1017

…

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."

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."

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**.

Dynamic Storage Management Example

```
void remove() {
  if (hlp = head) {
    head = hlp->next;
    free(hlp);
  }
}
insert( 'C' ); insert( 'B' ); insert( 'A' );
remove();
insert( 'X' );
```

data: 'A'
next: 0x1008

data: 'B'
next: 0x1013

data: 'C'
next: 0x0000

0x1000	0x1001	0x1002	0x1003	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		

Dynamic Storage Management Example

```
void remove() {
  if (hlp = head) {
    head = hlp->next;
    free(hlp);
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insert( 'C' ); insert( 'B' ); insert( 'A' );
remove();
insert( 'X' );
```

data: 'A'
next: 0x1008

data: 'B'
next: 0x1013

data: 'C'
next: 0x0000

0x1000	0x1001	0x1002	0x1003	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		

Dynamic Storage Management Example

```
void remove() {
  if (hlp = head) {
    head = hlp->next;
    free(hlp);
  }
}
insert( 'C' ); insert( 'B' ); insert( 'A' );
remove();
insert( 'X' );
```

data: 'B'
next: 0x1013

data: 'C'
next: 0x0000

0x1000	0x1001	0x1002	0x1003	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
			'C'	0x00	0x00		

Dynamic Storage Management Example

```c
void remove() {
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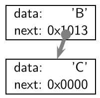
}
insert( 'C' ); insert( 'B' ); insert( 'A' );
remove();
insert( 'X' );
```



0x1000	0x1001 0x10	0x1002 0x08	0x1003 0x10	0x1004 0x0D	0x1005	0x1006	0x1007
0x1008 'B'	0x1009 0x10	0x100A 0x13	0x100B	0x100C	0x100D 'A'	0x100E 0x10	0x100F 0x08
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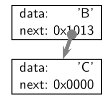

0x1000	0x1001 0x10	0x1002 0x08	0x1003 0x10	0x1004 0x0D	0x1005	0x1006	0x1007
0x1008 'B'	0x1009 0x10	0x100A 0x13	0x100B	0x100C	0x100D 'A'	0x100E 0x10	0x100F 0x08
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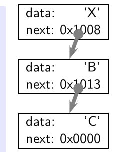
remove();
insert( 'X' );
```



0x1000	0x1001 0x10	0x1002 0x0D	0x1003 0x10	0x1004 0x0D	0x1005	0x1006	0x1007
0x1008 'B'	0x1009 0x10	0x100A 0x13	0x100B	0x100C	0x100D 'X'	0x100E 0x10	0x100F 0x08
0x1010	0x1011	0x1012	0x1013 'C'	0x1014 0x00	0x1015 0x00	0x1016	0x1017

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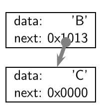


0x1000	0x1001 0x10	0x1002 0x08	0x1003 0x10	0x1004 0x0D	0x1005	0x1006	0x1007
0x1008 'B'	0x1009 0x10	0x100A 0x13	0x100B	0x100C	0x100D 'A'	0x100E 0x10	0x100F 0x08
0x1010 'X'	0x1011 0x10	0x1012 0x08	0x1013 'C'	0x1014 0x00	0x1015 0x00	0x1016	0x1017

Dynamic Linked List Iteration

```c
Node* find( char d ) {
  hlp = head;
  while (hlp) {
    if (hlp->data == d)
      break;
    hlp = hlp->next;
  }
  return hlp;
}
insert( 'C' ); insert( 'B' ); insert( 'A' );
find( 'B' ); // yields 0x1008
find( 'O' ); // yields 0x0000, aka. NULL
```

0x1000	0x1001 0x10	0x1002 0x0D	0x1003 0x10	0x1004 0x0D	0x1005	0x1006	0x1007
0x1008 'B'	0x1009 0x10	0x100A 0x13	0x100B	0x100C	0x100D 'A'	0x100E 0x10	0x100F 0x08
0x1010	0x1011	0x1012	0x1013 'C'	0x1014 0x00	0x1015 0x00	0x1016	0x1017

Pointers to Struct/Union — '.' vs. '->'

```c
typedef struct {
  int x;
  int y;
} coordinate;

coordinate pos = { 13, 27 };

coordinate* p = &pos;

int tmp;

tmp = (*p).x;
(*p).x = (*p).y;
(*p).y = tmp;

tmp = p->x;
p->x = p->y;
p->y = tmp;
```

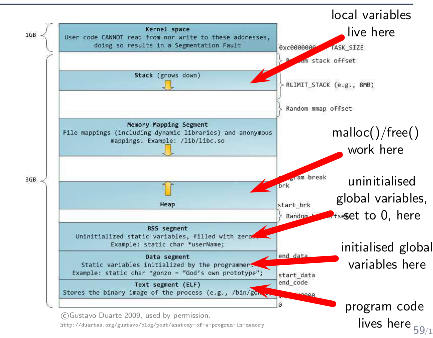
Storage Duration of Objects

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."

Example: Anatomy of a Linux Program in Memory



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http://duartes.org/gustavo/blog/post/anatomy-of-a-program-in-memory

Storage Duration "Automatic" (Simplified)

```
void h() { int y; y++; }
void g() { int x = 5; x++; }
int* f() { int c = 3; g(); h(); h(); return &c; }

int a = 27, b, *p;
p = f();
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

Storage Duration "Automatic" (Simplified)

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void h() { int y; y++; }
void g() { int x = 5; x++; }
int* f() { int c = 3; g(); h(); h(); return &c; }

int a = 27, b, *p;
p = f();
b = *p;
```

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

0x1000	0x1001	0x1002	0x1003	0x1004	0x1005	0x1006	0x1007
0x1008	0x1009	0x100A	0x100B	0x100C	0x100D	0x100E	0x100F
0x1010	0x1011	0x1012 0x00	0x1013 0x00	0x1014 0x00	0x1015 0x00	0x1016 0x00	0x1017 0x1B
		p		b		a	

Storage Duration "Automatic" (Simplified)

```
void h() { int y; y++; }
void g() { int x = 5; x++; }
int* f() { int c = 3; g(); h(); h(); return &c; }

int a = 27, b, *p;
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```

0x1000	0x1001	0x1002	0x1003	0x1004	0x1005	0x1006	0x1007
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		p		b		a	

Storage Duration “Automatic” (Simplified)

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void h() { int y; y++; }
void g() { int x = 5; x++; }
int* f() { int c = 3; g(); h(); h(); return &c; }

int a = 27, b, *p;
p = f();
b = *p;
```

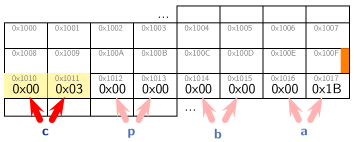

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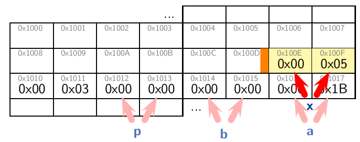
```
void h() { int y; y++; }
void g() { int x = 5; x++; }
int* f() { int c = 3; g(); h(); h(); return &c; }

int a = 27, b, *p;
p = f();
b = *p;
```



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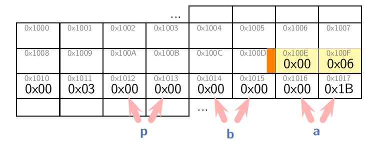

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```
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int* f() { int c = 3; g(); h(); h(); return &c; }

int a = 27, b, *p;
p = f();
b = *p;
```

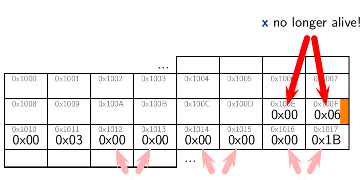

Storage Duration “Automatic” (Simplified)

```
void h() { int y; y++; }
void g() { int x = 5; x++; }
int* f() { int c = 3; g(); h(); h(); return &c; }

int a = 27, b, *p;
p = f();
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```
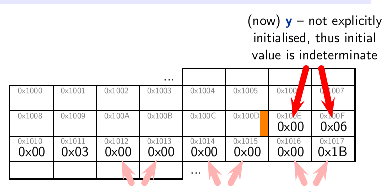
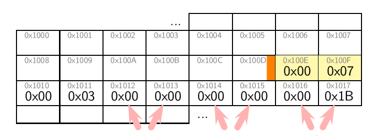



Storage Duration “Automatic” (Simplified)

```
void h() { int y; y++; }
void g() { int x = 5; x++; }
int* f() { int c = 3; g(); h(); h(); return &c; }

int a = 27, b, *p;
p = f();
b = *p;
```



Storage Duration “Automatic” (Simplified)

```c
void h() { int y; y++; }
void g() { int x = 5; x++; }
int* f() { int c = 3; g(); h(); h(); return &c; }

int a = 27, b, *p;
p = f();
b = *p;
```

y no longer alive!

0x1000	0x1001	0x1002	0x1003	0x1004	0x1005	0x1006	0x1007
0x1008	0x1009	0x100A	0x100B	0x100C	0x100D	0x100E: 0x00	0x100F: 0x07
0x1010: 0x00	0x1011: 0x03	0x1012: 0x00	0x1013: 0x00	0x1014: 0x00	0x1015: 0x00	0x1016: 0x00	0x1017: 0x1B

p b a

Storage Duration “Automatic” (Simplified)

```c
void h() { int y; y++; }
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int* f() { int c = 3; g(); h(); h(); return &c; }

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```

0x1000	0x1001	0x1002	0x1003	0x1004	0x1005	0x1006	0x1007
0x1008	0x1009	0x100A	0x100B	0x100C	0x100D	0x100E: 0x00	0x100F: 0x07
0x1010: 0x00	0x1011: 0x03	0x1012: 0x00	0x1013: 0x00	0x1014: 0x00	0x1015: 0x00	0x1016: 0x00	0x1017: 0x1B

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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

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int a = 27, b, *p;
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```

0x1000	0x1001	0x1002	0x1003	0x1004	0x1005	0x1006	0x1007
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int a = 27, b, *p;
p = f();
b = *p;
```
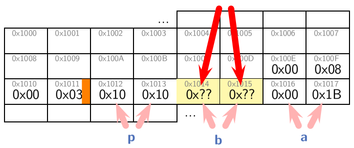

0x1000	0x1001	0x1002	0x1003	0x1004	0x1005	0x1006	0x1007
0x1008	0x1009	0x100A	0x100B	0x100C	0x100D	0x100E: 0x00	0x100F: 0x08
0x1010: 0x00	0x1011: 0x03	0x1012: 0x10	0x1013: 0x10	0x1014: 0x00	0x1015: 0x00	0x1016: 0x00	0x1017: 0x1B

p b a

Storage Duration "Automatic" (Simplified)

```
void h() { int y; y++; }
void g() { int x = 5; x++; }
int* f() { int c = 3; g(); h(); h(); return &c; }

int a = 27, b, *p;
p = f();
b = *p;
```

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



Storage Classes and Qualifiers

Storage Class Specifiers (6.7.1)

Storage Class Specifiers (6.7.1)

```
typedef char letter;

extern int x;
extern int f();

static int x; // two uses! (-> later)
static int f();


auto x; // "historic"

register y; // "historic"
```


Storage Class Specifiers: extern (6.7.1)

```
// not _defined_ here, "imported"...
//
extern int x;
extern void f();

// declared _and_ defined here, "exported" ...
//
int y;

int g() {
  x = y = 27;
  f();
}
```

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

Storage Class Specifiers: static (6.7.1)

```
// declared _and_ defined here,
// _not_ "exported" ...
//
static int x;
static void g();


int f() {
  static int a = 0;
  a++;
  printf( "%s\n", a );
}

f(); f(); f(); // yields 1, 2, 3
```

Qualifiers (6.7.3)

Qualifiers (6.7.3)

```
int x;

const int y;

volatile int z;

int* restrict p; // aliasing


const volatile int a;
```


Qualifiers (6.7.3)

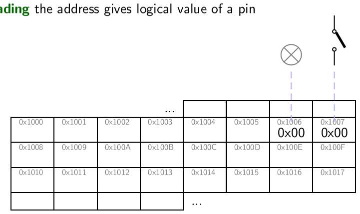
```
int x;

const int y;

volatile int z;

int* restrict p; // aliasing


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



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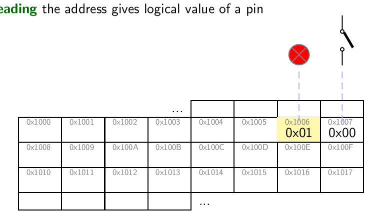

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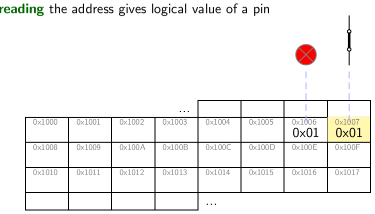

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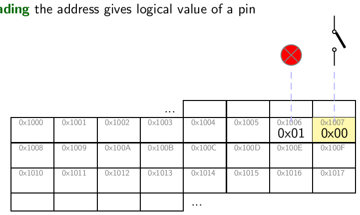

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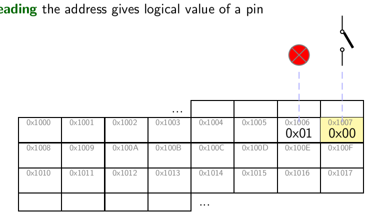


- The compiler does not know, "**memory is memory**".

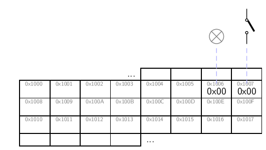
Qualifiers: `volatile` (6.7.3)

```c
volatile char* out = 0x1006;
volatile char* in = 0x1007;

out = 0x01; // switch lamp on

if (in & 0x01) { /* ... */ }

if ((in & 0x01) && (in & 0x01)) { /* ... */ }
```

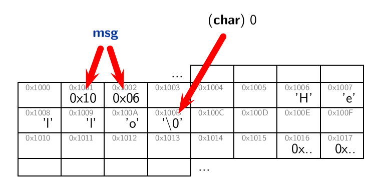


Strings & Input/Output

Strings

*Strings are 0-Terminated **char** Arrays*

```c
char* msg = "Hello";
char* str = msg;
```



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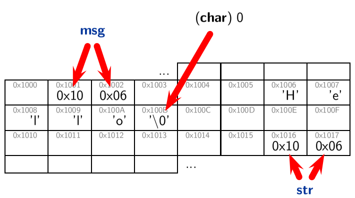

String Manipulation (Annex B)

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provides among others:

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  "[...] 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."

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  "The strcpy() function copies the string pointed to by s2, including **the terminating null byte** ('\0'), to the buffer pointed to by s1."

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None of these functions allocates memory!

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- 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

```
#include <stdio.h>

printf( "%s␣–␣%i␣–␣%f\n", "Hello", 27, 3.14 );
```


Tools & Modules

Hello, Again

```
#include <stdio.h>

int g( int x ) { return x/2; }

int f() { return g(1); }

int main() {
  printf( "Hello␣World.\n" );
  return f();
}
```

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

Zoom In: Preprocessing, Compiling, Linking

```
#include <stdio.h>

int g( int x ) { return x/2; }

int f() { return g(1); }

int main() {
  printf( "Hello␣World.\n" );
  return f();
}
```

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

Modules

```c
#include <stdio.h>

int g( int x ) {
  return x/2;
}

int f() {
  return g(1);
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```


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Split into:

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

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int g( int x ) {
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}
```

Split into:

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

g.h

```c
#ifndef G_H
#define G_H

extern int
  g( int x );
#endif
```

f.h

```c
#ifndef F_H
#define F_H

extern int
  f();
#endif
```

g.c

```c
#include "g.h"

int g( int x ) {
  return x/2;
}
```

f.c

```c
#include "g.h"
#include "f.h"

int f() {
  return g(1);
}
```

helloworld.c

```c
#include <stdio.h>
#include "f.h"

int main() {
  printf( "Hello World.\n" );
  return f();
}
```


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

```c
#ifndef G_H
#define G_H

extern int
  g( int x );
#endif
```

f.h

```c
#ifndef F_H
#define F_H

extern int
  f();
#endif
```

g.c

```c
#include "g.h"

int g( int x ) {
  return x/2;
}
```

f.c

```c
#include "g.h"
#include "f.h"

int f() {
  return g(1);
}
```

helloworld.c

```c
#include <stdio.h>
#include "f.h"

int main() {
  printf( "Hello World.\n" );
  return f();
}
```


Modules At Work

preprocess & compile:

- `% gcc -c g.c f.c \`
  `helloworld.c`
- `% ls *.o`
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- `% ./a.out`
- `Hello World.`

g.h

```c
#ifndef G_H
#define G_H

extern int
  g( int x );
#endif
```

f.h

```c
#ifndef F_H
#define F_H

extern int
  f();
#endif
```

g.c

```c
#include "g.h"

int g( int x ) {
  return x/2;
}
```

f.c

```c
#include "g.h"
#include "f.h"

int f() {
  return g(1);
}
```

helloworld.c

```c
#include <stdio.h>
#include "f.h"

int main() {
  printf( "Hi!\n" );
  return f();
}
```


Modules At Work

preprocess & compile:

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

```c
#ifndef G_H
#define G_H

extern int
  g( int x );
#endif
```

f.h

```c
#ifndef F_H
#define F_H

extern int
  f();
#endif
```

g.c

```c
#include "g.h"

int g( int x ) {
  return x/2;
}
```

f.c

```c
#include "g.h"
#include "f.h"

int f() {
  return g(1);
}
```

helloworld.c

```c
#include <stdio.h>
#include "f.h"

int main() {
  printf( "Hi!\n" );
  return f();
}
```

Preprocessing

helloworld.c

```c
#include <stdio.h>
#include "f.h"

int main() {
  printf( "Hello World.\n" );
  return f();
}
```

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

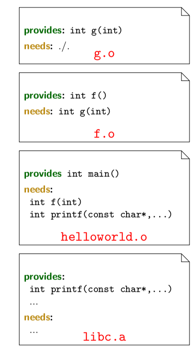
helloworld.i

```c
# 1 "helloworld.c"
# 1 "<command-line>"
# 1 "helloworld.c"
# 1 "/usr/include/stdio.h" 1 3 4
# 28 "/usr/include/stdio.h" 3 4
# 1 "/usr/include/features.h" 1 3 4
# 323 "/usr/include/features.h" 3 4
# 1 "/usr/include/x86_64-linux-gnu/bits/predefs.h" 1 3 4
# 324 "/usr/include/features.h" 2 3 4
# 356 "/usr/include/features.h" 3 4
# 1 "/usr/include/x86_64-linux-gnu/sys/cdefs.h" 1 3 4
# 359 "/usr/include/x86_64-linux-gnu/sys/cdefs.h" 3 4
# 1 "/usr/include/x86_64-linux-gnu/bits/wordsize.h" 1 3 4
# 360 "/usr/include/x86_64-linux-gnu/sys/cdefs.h" 2 3 4
# 357 "/usr/include/features.h" 2 3 4
# 388 "/usr/include/features.h" 3 4
# 1 "/usr/include/x86_64-linux-gnu/gnu/stubs.h" 1 3 4



# 1 "/usr/include/x86_64-linux-gnu/bits/wordsize.h" 1 3 4
# 5 "/usr/include/x86_64-linux-gnu/gnu/stubs.h" 2 3 4

[...]

extern int ftrylockfile (FILE *__stream) __attribute__ ((__nothrow__)) ;


extern void funlockfile (FILE *__stream) __attribute__ ((__nothrow__));
# 936 "/usr/include/stdio.h" 3 4

# 2 "helloworld.c" 2
# 1 "f.h" 1



extern int
  f();
# 3 "helloworld.c" 2

int main() {
  printf( "Hello World.\n" );
  return f();
}
```

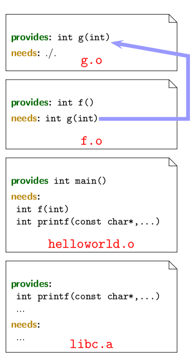

Preprocessing Directives (6.10)

```c
#include <stdio.h>
#include "battery.h"

#define PI 3.1415

#define DEBUG
#ifdef DEBUG
  fprintf( stderr, "honk\n" );
#endif

#if __GNUC__ >= 3
#  define __pure        __attribute__ ((pure))
#else
#  define __pure        /* no pure */
#endif

extern int f() __pure;
```

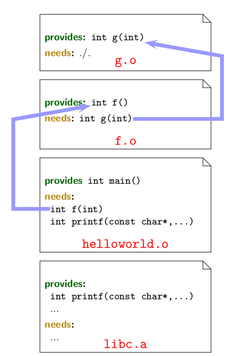

Linking



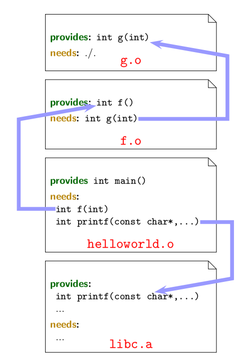
Linking



Linking



Linking



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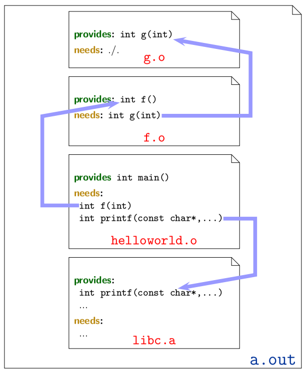


Compiler

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`

→ cf. `man gcc`

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`

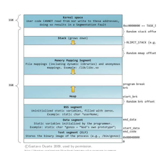
- **Build Utility**:

  `make`

  See battery controller exercise for an example.

Core Dumps

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



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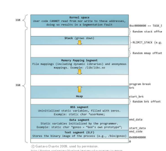

```
int main() {
  int *p;
  *p = 27;
  return 0;
}
```

```
% gcc -g core.c
% limit coredumpsize
coredumpsize 0 kbytes
% limit coredumpsize 1g
% ./a.out
Segmentation fault (core dumped)
% ls -lh core
-rw------- 1 user user 232K Feb 29 11:11 core
% gdb a.out core
GNU gdb (GDB) 7.4.1-debian
[...]
Core was generated by `./a.out'.
Program terminated with signal 11, Segmentation fault.
#0  0x00000000004004b4 in main () at core.c:3
3          *p = 27;
(gdb) p p
$1 = (int *) 0x0
(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)

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


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#include <assert.h>
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."

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  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).

abort (7.20.4.1)

```c
#include <stdlib.h>

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)

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>

```c
void f() {
  int* p = (int*)malloc(sizeof(int));

  if (!p)
    return;

  assert(p); // assume p is valid from here
  // ...
}

void g() {
  Node* p = find( 'a' );

  assert(p); // we inserted 'a' before
  // ...
}
```


Data Invariants with <assert.h>

```c
typedef struct {
  char* s;
  int n;
} str;

str* construct( char* s ) {
  str* x = (str*)malloc( sizeof(str) );
  // ...
  assert( (x->s == NULL && x->n == -1)
          || (x->n = strlen( x->s ) ) );
}
```


Pre/Post Conditions with <assert.h>

```c
int f( int x ) {
  assert( x != 0 ); // pre-condition

  int r = 10/x;

  assert( r == 10/x ); // post-condititon

  return r;
}
```

Loop Invariants with <assert.h>

```c
void f( int a[], int n ) {
  int i = 0;

  // holds before the loop
  assert( 0 <= i && i <= n );
  assert( i < 1 || a[i-1] == 0 );

  while (i < n) {
    // holds before each iteration
    assert( 0 <= i && i <= n );
    assert( i < 1 || a[i-1] == 0 );

    a[i++] = 0;
  }
  // holds after exiting the loop
  assert( 0 <= i && i <= n );
  assert( i < 1 || a[i-1] == 0 );

  return;
}
```


Old Variables, Ghost Variables

```c
void xorSwap( unsigned int* a, unsigned int* b ) {
#ifndef NDEBUG
  unsigned int *old_a = a, *old_b = b;
#endif
  assert( a && b ); assert( a != b ); // pre-condition

  *a = *a + *b;
  *b = *a - *b;
  *a = *a - *b;

  assert( *a == *old_b && *b == *old_a ); // post-con-
  assert( a == old_a && b == old_b );     // dition
}
```


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

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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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    - 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...

```
void f( short a, int b ) {
  a = b; // typing ok, but...
}

short a; // provisioning, implicit cast
if (++a < 0) { /* no */ }

if (++i > MAX_INT) {
  /* no */ }


int e = 0;

void set_error() { e++; }
void clear_error() { e = 0; }

void g() { if (e) { /* ... */ } }
```


Initialisation (6.7.8)

Initialisation (6.7.8)

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

```
void f() {
  int a;

  printf( "%i\n", a ); // surprise...
}
```


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.

```
char a[] = "hello", b[] = "hello"; // a == b?

i = 0; f( ++i, ++i, ++i ); // f(1,2,3)?

int g() { int a, b; } // &a > &b ?

int* p = malloc(sizeof(int));
int* q = malloc(sizeof(int)); // q > p?
```


Undefined Behaviour (J.2)

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)."

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

Undefined Behaviour (J.2)

More examples:

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

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- 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)

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- pointers that do not point into, or just beyond, the same array object are subtracted (6.5.6)
- An array subscript is out of range [...] (6.5.6)
- the program removes the definition of a macro whose name begins with an underscore and either an uppercase letter or another underscore (7.1.3)

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- pointers that do not point into, or just beyond, the same array object are subtracted (6.5.6)
- An array subscript is out of range [...] (6.5.6)
- the program removes the definition of a macro whose name begins with an underscore and either an uppercase letter or another underscore (7.1.3)
- etc. pp.

Null-Pointer

```c
int main() {
  int *p;
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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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  int *p = (int*)0x12345678;
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- Accessing memory which the process is not allowed to access is observed by the operating system.
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- 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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- etc. pp.

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.