Formal Methods for C

Seminar – Summer Semester 2014

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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
Function Pointers
the compiler chose to store the machine code of `f` at memory cell with address 0x1001
Calling Functions

```c
1 void f() { return; }
2 f();
```
Calling Functions

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

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

<table>
<thead>
<tr>
<th>0x1000</th>
<th>0x1001</th>
<th>0x1002</th>
<th>0x1003</th>
<th>0x1004</th>
<th>0x1005</th>
<th>0x1006</th>
<th>0x1007</th>
</tr>
</thead>
<tbody>
<tr>
<td>RET</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>0x1008</td>
<td>0x1009</td>
<td>0x100A</td>
<td>0x100B</td>
<td>0x100C</td>
<td>0x100D</td>
<td>0x100E</td>
<td>0x100F</td>
</tr>
<tr>
<td>CALL</td>
<td></td>
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<td></td>
<td>0x10</td>
<td>0x01</td>
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<tr>
<td>0x1010</td>
<td>0x1011</td>
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<td>0x1015</td>
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<td>0x1017</td>
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</tbody>
</table>
A Pointer to ‘f’ (16-bit Architecture)

```c
void f() {
    return;
}
f();
void (*p)() = &f;
```
### A Pointer to ‘f’ (16-bit Architecture)

A pointer to a function 'f' is declared as follows in the code:

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

f();

void (*p)() = &f;
```

The variable 'p' is a pointer to the function 'f'. In the context of a 16-bit architecture, the function's memory layout is shown:

```
<table>
<thead>
<tr>
<th>Address</th>
<th>0x1000</th>
<th>0x1001</th>
<th>0x1002</th>
<th>0x1003</th>
<th>0x1004</th>
<th>0x1005</th>
<th>0x1006</th>
<th>0x1007</th>
</tr>
</thead>
<tbody>
<tr>
<td>RET</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0x10</td>
<td>0x01</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CALL</td>
<td>0x1008</td>
<td>0x1009</td>
<td>0x100A</td>
<td>0x100B</td>
<td>0x100C</td>
<td>0x100D</td>
<td>0x100E</td>
<td>0x100F</td>
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<tr>
<td></td>
<td>0x1010</td>
<td>0x1011</td>
<td>0x1012</td>
<td>0x1013</td>
<td>0x1014</td>
<td>0x1015</td>
<td>0x1016</td>
<td>0x1017</td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
```

In the above table, `0x10` and `0x01` are the memory addresses for the function 'f'. The code snippet shows how to assign the address of 'f' to the pointer 'p'.
void f() {
    return;
}

f();

void (*p)() = &f;

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

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

```c
void f() {
    return;
}
f();
void (*p)() = &f;
(*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

<table>
<thead>
<tr>
<th>Address</th>
<th>Instruction</th>
<th>Address</th>
<th>Instruction</th>
<th>Address</th>
<th>Instruction</th>
<th>Address</th>
<th>Instruction</th>
</tr>
</thead>
<tbody>
<tr>
<td>0x1000</td>
<td>RET</td>
<td>0x1002</td>
<td></td>
<td>0x1003</td>
<td>0x10</td>
<td>0x1004</td>
<td>0x01</td>
</tr>
<tr>
<td>0x1008</td>
<td></td>
<td>0x1009</td>
<td></td>
<td>0x100A</td>
<td>CALL</td>
<td>0x100C</td>
<td>0x10</td>
</tr>
<tr>
<td>0x1010</td>
<td>MOV R</td>
<td>0x1012</td>
<td>0x04</td>
<td>0x1013</td>
<td>CALL R</td>
<td>0x1015</td>
<td>0x1016</td>
</tr>
</tbody>
</table>
```
Pointers vs. Arrays
Arrays

reserve some space for 5 chars...

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

...and let a point to that space
Arrays

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

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

![Memory Diagram](image-url)
Arrays

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

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

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

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

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

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

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

- `p` points to the first element of the array `a`.
- After the loop, the value of `p` points to the last element of the array `a`.
- The program modifies each element of the array with the character `o`.

---

Note: The table represents the memory layout of the characters in the array. Each cell represents a byte in memory, with the value inside the cell corresponding to the memory address and the character value. The `for` loop updates each element of the array with the character `o`. The diagram visually represents the memory layout and the movement of the pointer `p` through the array.
Arrays vs. Pointers

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

```
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'
0x1010 0x1011 0x1012 0x1013 0x1014 0x1015 0x1016 0x1017
```

- 2014-04 - pointers -

44/125
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';
```

![Memory layout diagram]

- 0x1000 - 0x1001 - 0x1002 - 0x1003 - 0x1004 - 0x1005 - 0x1006 - 0x1007
- 0x1008 - 0x1009 - 0x100A - 0x100B - 0x100C - 0x100D - 0x100E - 0x100F
- ...
reserve some space for 3 `int`s...

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

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

<p>| | | | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0x1000</td>
<td>0x1001</td>
<td>0x1002</td>
<td>0x1003</td>
<td>0x1004</td>
<td>0x1005</td>
<td>0x1006</td>
<td>0x1007</td>
<td></td>
</tr>
<tr>
<td>0x10</td>
<td>0x08</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>0x1008</td>
<td>0x1009</td>
<td>0x100A</td>
<td>0x100B</td>
<td>0x100C</td>
<td>0x100D</td>
<td>0x100E</td>
<td>0x100F</td>
<td></td>
</tr>
<tr>
<td>0x00</td>
<td>0x0A</td>
<td>0x00</td>
<td>0x08</td>
<td>0x12</td>
<td>0x34</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0x1010</td>
<td>0x1011</td>
<td>0x1012</td>
<td>0x1013</td>
<td>0x1014</td>
<td>0x1015</td>
<td>0x1016</td>
<td>0x1017</td>
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<td></td>
<td></td>
<td></td>
<td>...</td>
<td></td>
</tr>
</tbody>
</table>

...
Integer Arrays

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

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

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

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

```
<p>| | | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
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<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0x100</td>
<td>0x1001</td>
<td>0x1002</td>
<td>0x1003</td>
<td>0x1004</td>
<td>0x1005</td>
<td>0x1006</td>
<td>0x1007</td>
</tr>
<tr>
<td>0x10</td>
<td>0x08</td>
<td>0x00</td>
<td>0x03</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0x00</td>
<td>0x27</td>
<td>0x00</td>
<td>0x27</td>
<td>0x00</td>
<td>0x00</td>
<td>0x27</td>
<td></td>
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<td>0x00</td>
<td>0x00</td>
<td>0x27</td>
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<td>0x00</td>
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<tr>
<td>0x1010</td>
<td>0x1011</td>
<td>0x1012</td>
<td>0x1013</td>
<td>0x1014</td>
<td>0x1015</td>
<td>0x1016</td>
<td>0x1017</td>
</tr>
<tr>
<td>...</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
```
```
int a [3] = { 10, 010, 0x1234 };
int* p = a;
for (int i = 0; i < 3; ++p)
    *p = 0x3421;
```
### Integer Arrays vs. Pointers

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

<table>
<thead>
<tr>
<th>Offsets</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>0x000</td>
<td>0x10</td>
</tr>
<tr>
<td>0x001</td>
<td>0x10</td>
</tr>
<tr>
<td>0x002</td>
<td>0x10</td>
</tr>
<tr>
<td>0x003</td>
<td>0x10</td>
</tr>
<tr>
<td>0x004</td>
<td>0x10</td>
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<td>0x005</td>
<td>0x10</td>
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<tr>
<td>0x006</td>
<td>0x10</td>
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<tr>
<td>0x007</td>
<td>0x10</td>
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<tr>
<td>0x008</td>
<td>0x10</td>
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<td>0x009</td>
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<td>0x012</td>
<td>0x10</td>
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<td>0x013</td>
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<td>0x014</td>
<td>0x10</td>
</tr>
<tr>
<td>0x015</td>
<td>0x10</td>
</tr>
<tr>
<td>0x016</td>
<td>0x10</td>
</tr>
<tr>
<td>0x017</td>
<td>0x10</td>
</tr>
</tbody>
</table>

- Data points: 0x0100, 0x0101, 0x0102, 0x0103, 0x0104, 0x0105, 0x0106, 0x0107, 0x0108, 0x0109, 0x010A, 0x010B, 0x010C, 0x010D, 0x010E, 0x010F

- Pointer `p` points to `a[0]` initially.

- `for` loop increments `p` by 1 at each iteration.

- After the loop, `p` points to `a[2]`.

- The values stored at each offset can be seen in the table above.
Integer Arrays vs. Pointers

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

![Diagram showing memory layout of arrays and pointers](attachment:memory-diagram.png)
### Integer Arrays vs. Pointers

The code snippet demonstrates the difference in accessing array elements using an array and a pointer.

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

In the table, `p` is a pointer to the first element of `a`. Each cell represents the memory address of each element, with the value of the element shown in the corresponding cell.
Integer Arrays vs. Pointers

```c
int a[3] = { 10, 010, 0x1234 };
int* p = a;
for (int i = 0; i < 3; ++p)
    *p = 0x3421;
```
Pointers to 'void', Pointer Arithmetic
**Pointer to ’void’**

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

int* p = a;

void* q = a;

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

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

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

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

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

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

for (int i = 0; i < 3; ++i) {
    p++;
    q++;
}
```
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.

```c
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

```c
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

```c
void f ( int x, int y ) {
    x++, y++; // Points to same address after increment
}
void g( int* p, int* q ) {
    (*p)++, (*q)++; // Points to different addresses after increment
}
int a = 2, b = 5;
f( a, b );
g( &a, &b );
```

The diagram illustrates how the variables `x` and `y` are incremented within the `f` function, while `p` and `q` are incremented within the `g` function. The addresses and values of `a`, `b`, `x`, `p`, and `q` are shown in the table.
Call By Reference with Pointers

```c
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

```c
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 ) ;
```

<p>| | | | | | | | |</p>
<table>
<thead>
<tr>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0x1000</td>
<td>0x1001</td>
<td>0x1002</td>
<td>0x1003</td>
<td>0x1004</td>
<td>0x1005</td>
<td>0x1006</td>
<td>0x1007</td>
</tr>
<tr>
<td>0x00</td>
<td>0x02</td>
<td>0x00</td>
<td>0x05</td>
<td></td>
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</tbody>
</table>
Call By Reference with Pointers

```c
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);
```
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

```c
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 );
```
```c
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);
```

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<tr>
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</tbody>
</table>
...
Dynamic Storage & Storage Duration
Dynamic Storage Allocation
A Linked List

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

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

```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');
```

```
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 ..
...```
```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' );
```

```
0x1000 0x1001 0x1002 0x1003 0x1004 0x1005 0x1006 0x1007
0x00 0x00 0x10 0x13
0x1008 0x1009 0x100A 0x100B 0x100C 0x100D 0x100E 0x100F
0x1010 0x1011 0x1012 0x1013 'C' 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');

...
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');
ninsert('B');
ninsert('A');
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');

<table>
<thead>
<tr>
<th>0x1000</th>
<th>0x1001</th>
<th>0x1002</th>
<th>0x1003</th>
<th>0x1004</th>
<th>0x1005</th>
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</table>

...
```c
# Dynamic Storage Allocation

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

Node *head = 0, *hlp;

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

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

---

data: 'C'
next: 0x0000
```
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' );

data: 'C'
next: 0x0000

<table>
<thead>
<tr>
<th>0x1000</th>
<th>0x1001</th>
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<th>0x1003</th>
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<td>0x100D</td>
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<tr>
<td>'B'</td>
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</tbody>
</table>
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**

```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

<table>
<thead>
<tr>
<th>0x1000</th>
<th>0x1001</th>
<th>0x1002</th>
<th>0x1003</th>
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<td>'C'</td>
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</table>
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' );

<table>
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<tr>
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<th>Value</th>
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<tr>
<td>0x1001</td>
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<td>0x1016</td>
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<td>0x1017</td>
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<td>...</td>
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</tr>
</tbody>
</table>

Data: 'B' located at 0x01013
Next: 0x0000

Data: 'C' located at 0x01000
Next: 0x0000
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' );

<table>
<thead>
<tr>
<th>0x1000</th>
<th>0x1001</th>
<th>0x1002</th>
<th>0x1003</th>
<th>0x1004</th>
<th>0x1005</th>
<th>0x1006</th>
<th>0x1007</th>
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<td>'C'</td>
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</tr>
</tbody>
</table>
```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');
```

```
<table>
<thead>
<tr>
<th>Address</th>
<th>0x1000</th>
<th>0x1001</th>
<th>0x1002</th>
<th>0x1003</th>
<th>0x1004</th>
<th>0x1005</th>
<th>0x1006</th>
<th>0x1007</th>
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<td></td>
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<td>0x10</td>
<td>0x0D</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>'B'</td>
<td>0x1009</td>
<td>0x100A</td>
<td>0x13</td>
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<td>0x1010</td>
<td>0x1011</td>
<td>0x1012</td>
<td>0x1013</td>
<td>'C'</td>
<td>0x00</td>
<td>0x00</td>
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</tr>
</tbody>
</table>

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

insert( 'C' ); insert( 'B' ); insert( 'A' );
remove();
insert( 'X' );
Dynamic Storage Management Example

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

```
0x1000 0x1001 0x1002 0x1003 0x1004 0x1005 0x1006 0x1007  ...  
0x1008 0x1009 0x100A 0x100B 0x100C 0x100D 0x100E 0x100F  
    'B'   0x10  0x10  0x10  0x10  0x10  0x10  0x10  0x10  
    0x1010 0x1011 0x1012 0x1013 0x1014 0x1015 0x1016 0x1017  
    'C'   0x00  0x00  0x00  0x00  0x00  0x00  0x00  0x00  
    0x1018 0x1019 0x101A 0x101B 0x101C 0x101D 0x101E 0x101F  
      ...  ...  ...  ...  ...  ...  ...  ...
```

- data: 'B'
  next: 0x1013

- data: 'C'
  next: 0x0000
void remove() {
    if (hlp = head) {
        head = hlp->next;
        free(hlp);
    }
}

insert('C'); insert('B'); insert('A');
remove();
insert('X');
Dynamic Storage Management Example

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

---

```

<table>
<thead>
<tr>
<th>0x1000</th>
<th>0x1001</th>
<th>0x1002</th>
<th>0x1003</th>
<th>0x1004</th>
<th>0x1005</th>
<th>0x1006</th>
<th>0x1007</th>
</tr>
</thead>
<tbody>
<tr>
<td>0x10</td>
<td>0x08</td>
<td>0x10</td>
<td>0x0D</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>'B'</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>0x1008</th>
<th>0x1009</th>
<th>0x100A</th>
<th>0x100B</th>
<th>0x100C</th>
<th>0x100D</th>
<th>0x100E</th>
<th>0x100F</th>
</tr>
</thead>
<tbody>
<tr>
<td>0x10</td>
<td>0x13</td>
<td></td>
<td></td>
<td></td>
<td>'A'</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>0x1010</th>
<th>0x1011</th>
<th>0x1012</th>
<th>0x1013</th>
<th>0x1014</th>
<th>0x1015</th>
<th>0x1016</th>
<th>0x1017</th>
</tr>
</thead>
<tbody>
<tr>
<td>0x10</td>
<td>0x08</td>
<td></td>
<td>'C'</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
```

---

data: 'B'
next: 0x1013

---

data: 'C'
ext: 0x0000
Dynamic Linked List Iteration

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

coordinate pos = { 13, 27 };

cordinate* p = &pos;

int tmp;  \textcolor{red}{\texttt{\textcolor{blue}{tmp = pos.x;}}}

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

- Local variables live here
- malloc()/free() work here
- Uninitialised global variables, set to 0, here
- Initialised global variables here
- Program code lives here

©Gustavo Duarte 2009, used by permission.
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.)
### 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;
```

---

<table>
<thead>
<tr>
<th>0x1000</th>
<th>0x1001</th>
<th>0x1002</th>
<th>0x1003</th>
<th>0x1004</th>
<th>0x1005</th>
<th>0x1006</th>
<th>0x1007</th>
</tr>
</thead>
<tbody>
<tr>
<td>0x1008</td>
<td>0x1009</td>
<td>0x100A</td>
<td>0x100B</td>
<td>0x100C</td>
<td>0x100D</td>
<td>0x100E</td>
<td>0x100F</td>
</tr>
<tr>
<td>0x1010</td>
<td>0x1011</td>
<td>0x1012</td>
<td>0x1013</td>
<td>0x1014</td>
<td>0x1015</td>
<td>0x1016</td>
<td>0x1017</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>

- **p**: Pointer to `f()`
- **b**: Value of `c`
- **a**: Value of `a`
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;
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;
```c
int a = 27, b, *p;
p = f();
b = *p;
```

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

x no longer alive!
## 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;
```

### Note:

- `y` – not explicitly initialised, thus initial value is indeterminate

---

Table showing memory allocation:

<p>| | | | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0x1000</td>
<td>0x1001</td>
<td>0x1002</td>
<td>0x1003</td>
<td>0x1004</td>
<td>0x1005</td>
<td>0x1006</td>
<td>0x1007</td>
<td></td>
</tr>
<tr>
<td>0x1008</td>
<td>0x1009</td>
<td>0x100A</td>
<td>0x100B</td>
<td>0x100C</td>
<td>0x100D</td>
<td>0x100E</td>
<td>0x100F</td>
<td></td>
</tr>
<tr>
<td>0x1010</td>
<td>0x1011</td>
<td>0x1012</td>
<td>0x1013</td>
<td>0x1014</td>
<td>0x1015</td>
<td>0x1016</td>
<td>0x1017</td>
<td></td>
</tr>
<tr>
<td>0x00</td>
<td>0x03</td>
<td>0x00</td>
<td>0x00</td>
<td>0x00</td>
<td>0x00</td>
<td>0x00</td>
<td>0x1B</td>
<td></td>
</tr>
</tbody>
</table>

...
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!
```

The image shows a memory diagram with addresses `0x1000` through `0x1017`, where `p`, `b`, and `a` point to different locations in memory. The memory layout is as follows:

- `0x1000` to `0x1007`: Variables `a` and `b`.
- `0x1008` to `0x100F`: Array of integers.
- `0x1010` to `0x1017`: Variables `p`, `b`, and `a`.
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;
```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;
```
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;
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;
```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;
```
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)
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)

```c
// 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)

```c
// 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)
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)
**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**

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

![Memory Address Diagram](image-url)
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)) { /* ... */ }

...
Strings & Input/Output
Strings
Strings are 0-Terminated char Arrays

1. `char* msg = "Hello";`
2. `char* str = msg;`
Strings are 0-Terminated `char` Arrays

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

<table>
<thead>
<tr>
<th>char</th>
<th>msg</th>
<th>str</th>
</tr>
</thead>
<tbody>
<tr>
<td>0x10</td>
<td>0x10</td>
<td>0x10</td>
</tr>
<tr>
<td>0x06</td>
<td>0x06</td>
<td>0x06</td>
</tr>
<tr>
<td>'H'</td>
<td>'H'</td>
<td>'H'</td>
</tr>
<tr>
<td>'e'</td>
<td>'e'</td>
<td>'e'</td>
</tr>
<tr>
<td>'l'</td>
<td>'l'</td>
<td>'l'</td>
</tr>
<tr>
<td>'l'</td>
<td>'l'</td>
<td>'l'</td>
</tr>
<tr>
<td>'o'</td>
<td>'o'</td>
<td>'o'</td>
</tr>
<tr>
<td>'\0'</td>
<td>'\0'</td>
<td>'\0'</td>
</tr>
</tbody>
</table>

...
String Manipulation (Annex B)

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

printf("%s-%i-%f\n", "Hello", 27, 3.14);
Tools & Modules
Hello, Again

```c
#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.
%
#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.
- %
```c
#include <stdio.h>

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

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

int main() {
    printf( "Hello World.\n" );
    return f();
}
```
#include <stdio.h>

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

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

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

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

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

```c
#include <stdio.h>

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

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

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

```c
#include <stdio.h>

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

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

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

```c
#include "g.h"

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

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

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

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

```c
#include "f.h"
int f() {
    return g(1);
}
```

```c
#include <stdio.h>
#include "f.h"
int main() {
    printf("Hi!\n");
    return f();
}
```
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!
```c
#include <stdio.h>
#include "f.h"

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

- `% gcc -E helloworld.c -o helloworld.i`
```c
#include <stdio.h>
#include "battery.h"

#define PI 3.1415

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

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

extern int f() __pure;
```
provides: int \textit{g}(\textit{int})
needs: ./

provides: int \textit{f}()
needs: int \textit{g}(\textit{int})

provides int \textit{main}()
needs:
  int \textit{f}(\textit{int})
  int \textit{printf}(\textit{const char*},...)

provides:
  int \textit{printf}(\textit{const char*},...)
  ...
needs:
  ...
  \textit{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*,...)
  - ... `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

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

provides: int f()
needs: int g(int)

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

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

provides:
  int g(int)
neela: .g.o
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

a.out
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 lib**library**.\{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.
Core Dumps

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

```c
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 Segmentation fault.
#0 0x00000000004004b4 in int (*)() at core.c:3
0x0000000000000000
(gdb)
$1 = (int *)0x0
(gdb)
```
Formal Methods for C
Correctness and Requirements
Correctness

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

Examples:
- $\varphi_1$: the return value is 10 divided by parameter (if parameter not 0)
- $\varphi_2$: the value of variable $x$ is “always” strictly greater than 3
- $\varphi_3$: 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?
```c
#include <assert.h>
void assert( /* scalar */ expression );
```
“The assert macro puts diagnostic tests into programs; [...] When it is executed, if \texttt{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 \texttt{abort} function.”
"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).
#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-condition

    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;
}
```
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-condition
  assert( a == old_a && b == old_b ); // dition
}
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)
“The program has been verified.” tells us
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  • Which specifications have been considered?
Dependability

- “The program has been verified.” tells us not very much.
- One wants to know (and should state):
  - **Which specifications** have been considered?
  - 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”!

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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
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)
“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
• Not specific to C...

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

```c
void f() {
    int a;
    printf( "%i\n", a ); // surprise...
}
```
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.

```c
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)
“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.”
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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- etc. pp.
Null-Pointer

```c
int main() {
    int *p;
    *p = 27;
    return 0;
}
```
Null-Pointer

- "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)
int main() {
    int *p = (int*)0x12345678;
    *p = 27;

    *(int*)((void*)p + 1) = 13;
    return 0;
}


Modern operating systems provide **memory protection**.

Accessing memory which the process is not allowed to access is observed by the operating system.

Typically an instance of “accessing an object outside its lifetime”.

**But:** other way round does not hold, accessing an object outside its lifetime does not imply a 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.
Implementation-Defined Behaviour (J.3)
“A conforming implementation is required to document its choice of behavior in each of the areas listed in this subclause. The following are implementation-defined:”
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- J.3.2 Environment, e.g.
  The set of signals, their semantics, and their default handling (7.14).
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  The result of converting a pointer to an integer or vice versa (6.3.2.3).
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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.”