Formal Methods for C

Seminar – Summer Semester 2014

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Content

Function Pointers

Functions in the System's Memory

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

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

Calling Functions

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


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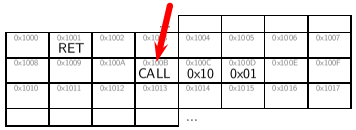
```

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



A Pointer to ‘f’ (16-bit Architecture)

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2 f();
3 void (*p) () = &f;
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‘p’ is a variable which stores the address of a function (here: of ‘f’)

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

…

Dereference Function Pointers

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

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

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

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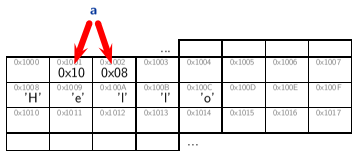
Pointers vs. Arrays

Arrays

reserve some space for 5 **chars**...

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

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



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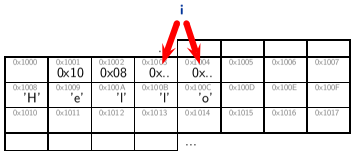

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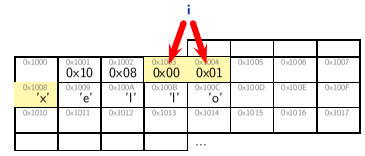

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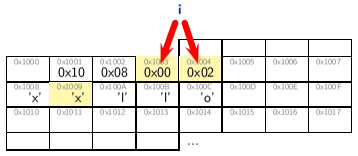

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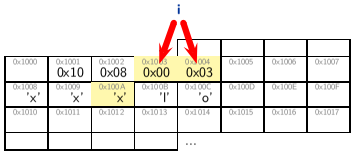

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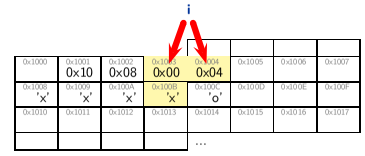

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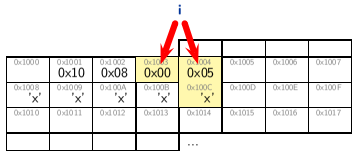

Arrays vs. Pointers

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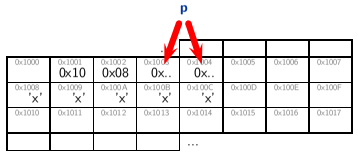

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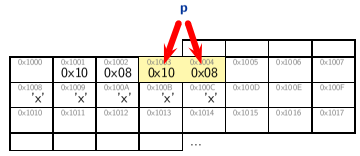

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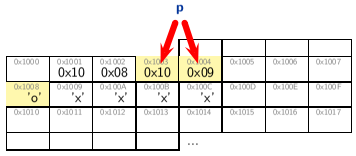

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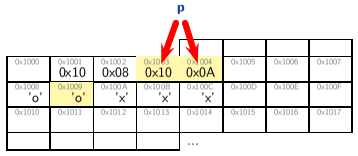

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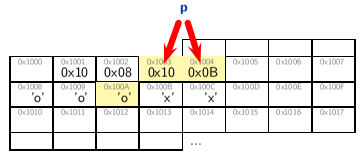

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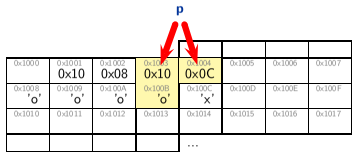

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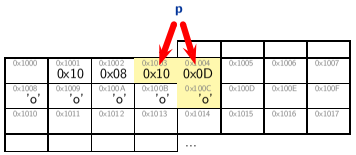

Integer Arrays

reserve some space for 3 **int**s...

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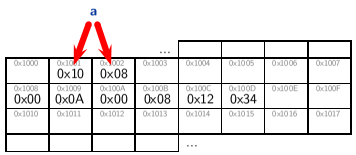

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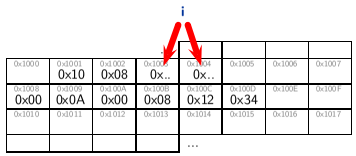

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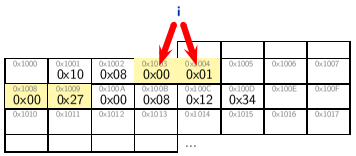

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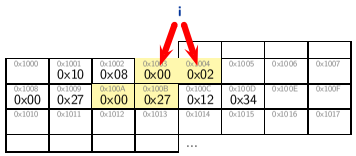

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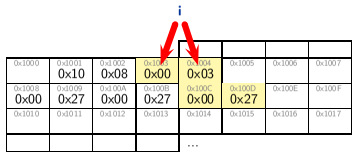

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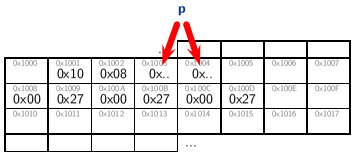

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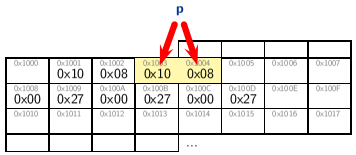

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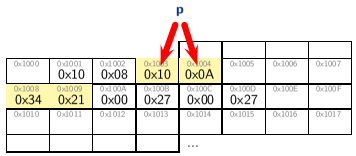

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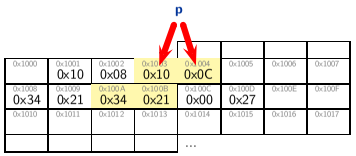

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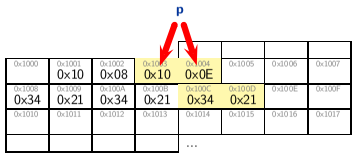

Pointers to 'void', Pointer Arithmetic

Pointer to 'void'

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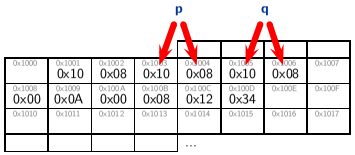

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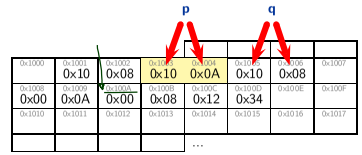

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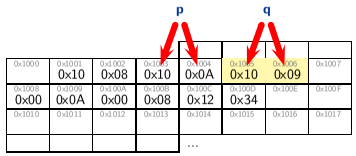

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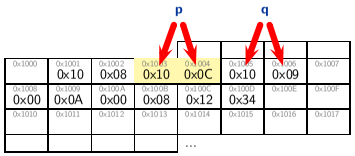

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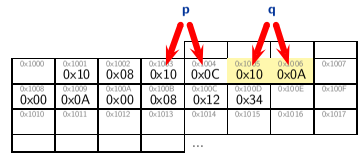

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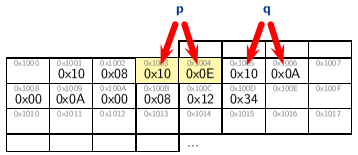

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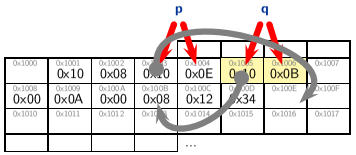


Pointers: Observation

- 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.

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


Pointer Arithmetic

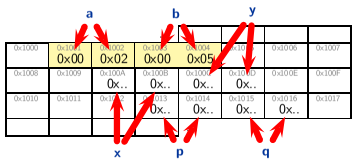
```
1  int[3] a = { 10, 010, 0x1234 }, i = 0;
2
3  int* p = a; // not &a !
4
5  if (a[0] == *p) i++; ✓
6  if (a[1] == *(p+1)) i++; ✓
7  if (a[2] == *(p+2)) i++; ✓
8
9  if (&(a[2]) - p == 2) i++; ✓
10
11 void* q = a;
12
13 if (a[2] == *((int*)(q + (2 * sizeof(int))))) i++; ✓
14
15 // i == 5
```

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

Pointers for Call By Reference

Call By Reference with Pointers

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



Call By Reference with Pointers

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

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

Call By Reference with Pointers

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

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

Call By Reference with Pointers

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

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

Call By Reference with Pointers

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

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

Call By Reference with Pointers

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

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

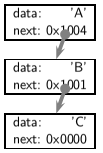
Call By Reference with Pointers

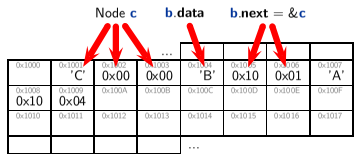
```
1 void f( int x, int y ) {
2   x++, y++;
3 }
4 void g( int* p, int* q ) {
5   (*p)++, (*q)++;
6 }
7 int a = 2, b = 5;
8 f( a, b );
9 g( &a, &b );
```

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

A Linked List

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



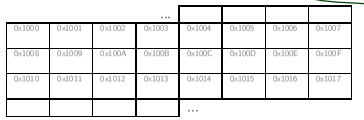



```
1  typedef struct Node {
2    char data; struct Node* next; } Node;
3
4  Node *head = 0, *hlp;
5
6  void insert( char d ) {
7    hlp = (Node*)malloc( sizeof(Node) );
8    hlp->data = d;
9    hlp->next = head;
10   head = hlp;
11 }
12
13 insert( 'C' );
14 insert( 'B' );
15 insert( 'A' );
```

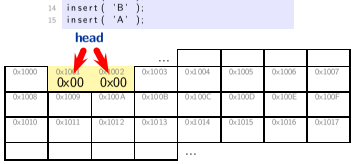
"man allocate"

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

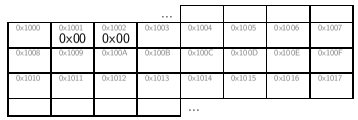
"man page reference section"




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




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



Dynamic Storage Allocation

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

hlp

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

Dynamic Storage Allocation

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

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

Dynamic Storage Allocation

```
1  typedef struct Node {
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11 }
12
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15 insert( 'A' );
```

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

Dynamic Storage Allocation

```
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10   head = hlp;
11 }
12
13 insert( 'C' );
14 insert( 'B' );
15 insert( 'A' );
```

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

Dynamic Storage Allocation

```
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3
4  Node *head = 0, *hlp;
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9    hlp->next = head;
10   head = hlp;
11 }
12
13 insert( 'C' );
14 insert( 'B' );
15 insert( 'A' );
```

data: 'C'
next: 0x0000

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

Dynamic Storage Allocation

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

data: 'C'
next: 0x0000

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

Dynamic Storage Allocation

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1  typedef struct Node {
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10   head = hlp;
11 }
12
13 insert( 'C' );
14 insert( 'B' );
15 insert( 'A' );
```

data: 'C'
next: 0x0000

			...				
0x1000	0x1001	0x1002	0x1003	0x1004	0x1005	0x1006	0x1007
	0x10	0x13	0x10	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

```
1  typedef struct Node {
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9    hlp->next = head;
10   head = hlp;
11 }
12
13 insert( 'C' );
14 insert( 'B' );
15 insert( 'A' );
```

data: 'C'
next: 0x0000

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

Dynamic Storage Allocation

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

data: 'C'
next: 0x0000

			...				
0x1000	0x1001	0x1002	0x1003	0x1004	0x1005	0x1006	0x1007
	0x10	0x13	0x10	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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1  typedef struct Node {
2    char data; struct Node* next; } Node;
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9    hlp->next = head;
10   head = hlp;
11 }
12
13 insert( 'C' );
14 insert( 'B' );
15 insert( 'A' );
```

data: 'C'
next: 0x0000

			...				
0x1000	0x1001	0x1002	0x1003	0x1004	0x1005	0x1006	0x1007
	0x10	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

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

```
1  typedef struct Node {
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8    hlp->data = d;
9    hlp->next = head;
10   head = hlp;
11 }
12
13 insert( 'C' );
14 insert( 'B' );
15 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

```
1  typedef struct Node {
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12
13 insert( 'C' );
14 insert( 'B' );
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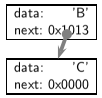
```



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

Dynamic Storage Allocation

```
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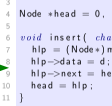
9    hlp->next = head;
10   head = hlp;
11 }
12
13 insert( 'C' );
14 insert( 'B' );
15 insert( 'A' );
```



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

Dynamic Storage Allocation

```
1  typedef struct Node {
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12
13 insert( 'C' );
14 insert( 'B' );
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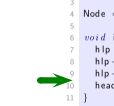
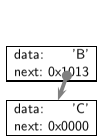
```



			...				
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 Allocation

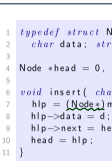
```
1  typedef struct Node {
2    char data; struct Node* next; } Node;
3
4  Node *head = 0, *hlp;
5
6  void insert( char d ) {
7    hlp = (Node*)malloc( sizeof(Node) );
8    hlp->data = d;
9    hlp->next = head;
10   head = hlp;
11 }
12
13 insert( 'C' );
14 insert( 'B' );
15 insert( 'A' );
```



			...				
0x1000	0x1001	0x1002	0x1003	0x1004	0x1005	0x1006	0x1007
	0x10	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 Allocation

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



			...				
0x1000	0x1001	0x1002	0x1003	0x1004	0x1005	0x1006	0x1007
	0x10	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

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);
  }
}
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

```
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

```
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

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

data: 'X'
next: 0x1008

data: 'B'
next: 0x1013

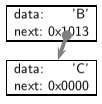
data: 'C'
next: 0x0000

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

...

Dynamic Storage Management Example

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



			...				
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
'X'	0x10	0x08	'C'	0x00	0x00		
				...			

Dynamic Linked List Iteration

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

			...				
0x1000	0x1001	0x1002	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		
				...			

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

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

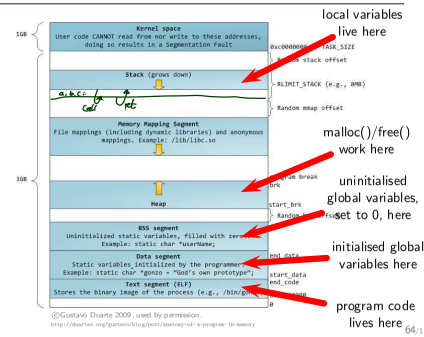

Storage Duration of Objects

Storage Duration of Objects (6.2.4)

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

"If an object is referred to outside of its lifetime, **the behavior is undefined**. The value of a pointer becomes indeterminate when the object it points to reaches the end of its lifetime."

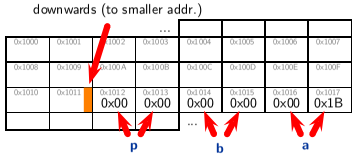
Example: Anatomy of a Linux Program in Memory



Storage Duration "Automatic" (Simplified)

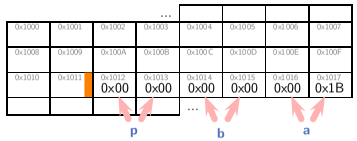
```
1 void h() { int y; y++; }
2 void g() { int x = 5; x++; }
3 int* f() { int c = 3; g(); h(); h(); return &c; }
4
5 int a = 27, b, *p;
6 p = f();
7 b = *p;
```

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



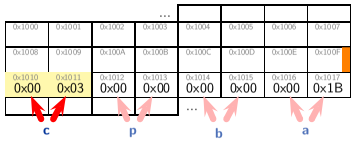
Storage Duration "Automatic" (Simplified)

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



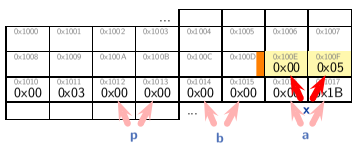
Storage Duration "Automatic" (Simplified)

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



Storage Duration "Automatic" (Simplified)

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



Storage Duration "Automatic" (Simplified)

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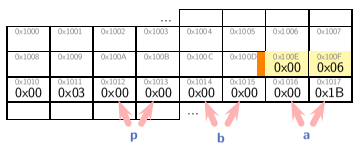
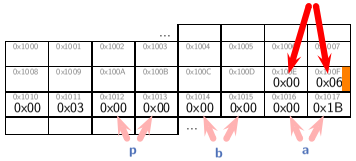
```



Storage Duration "Automatic" (Simplified)

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

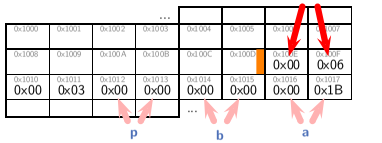
x no longer alive!



Storage Duration "Automatic" (Simplified)

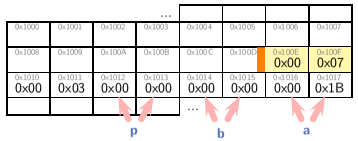
```
1  void h() { int y; y++; }
2  void g() { int x = 5; x++; }
3  int* f() { int c = 3; g(); h(); h(); return &c; }
4
5  int a = 27, b, *p;
6  p = f();
7  b = *p;
```

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



Storage Duration "Automatic" (Simplified)

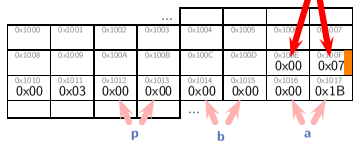
```
1  void h() { int y; y++; }
2  void g() { int x = 5; x++; }
3  int* f() { int c = 3; g(); h(); h(); return &c; }
4
5  int a = 27, b, *p;
6  p = f();
7  b = *p;
```



Storage Duration "Automatic" (Simplified)

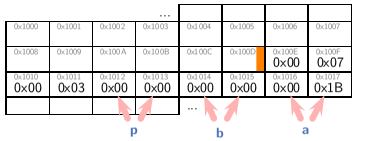
```
1  void h() { int y; y++; }
2  void g() { int x = 5; x++; }
3  int* f() { int c = 3; g(); h(); h(); return &c; }
4
5  int a = 27, b, *p;
6  p = f();
7  b = *p;
```

y no longer alive!



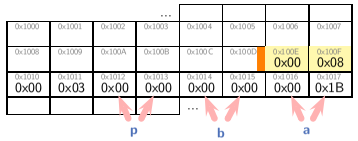
Storage Duration "Automatic" (Simplified)

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



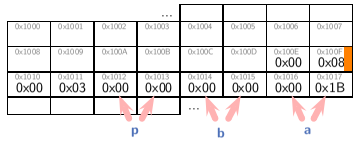
Storage Duration "Automatic" (Simplified)

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



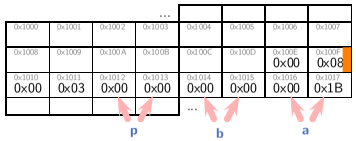
Storage Duration "Automatic" (Simplified)

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



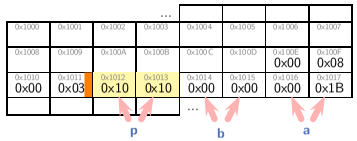
Storage Duration “Automatic” (Simplified)

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



Storage Duration “Automatic” (Simplified)

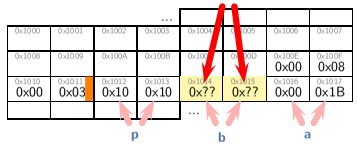
```
1 void h() { int y; y++; }
2 void g() { int x = 5; x++; }
3 int* f() { int c = 3; g(); h(); h(); return &c; }
4
5 int a = 27, b, *p;
6 p = f();
7 b = *p;
```



Storage Duration “Automatic” (Simplified)

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

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



Storage Classes and Qualifiers

Storage Class Specifiers (6.7.1)

Storage Class Specifiers (6.7.1)

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

int int

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)

Qualifiers (6.7.3)

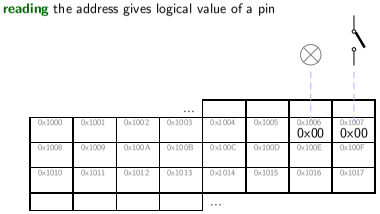
```c
int x;

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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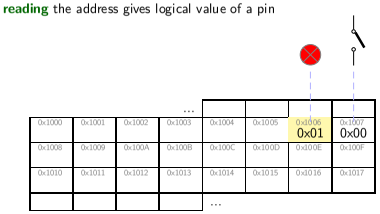

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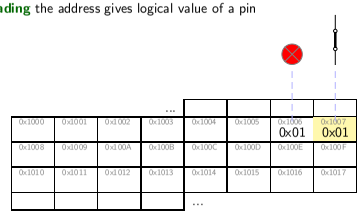

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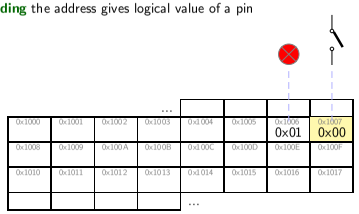

Excursion: Memory Mapped I/O

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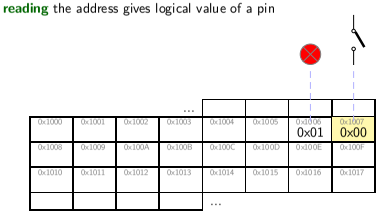
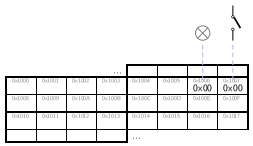


- The compiler does not know, "**memory is memory**".

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)) { /* ... */ }
```

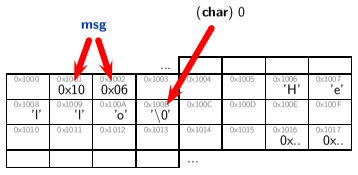


Strings & Input/Output

Strings

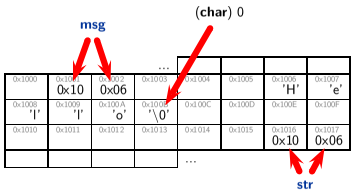
*Strings are 0-Terminated **char** Arrays*

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



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

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



String Manipulation (Annex B)

 # include<string.h>

provides among others:

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

None of these functions allocates memory!

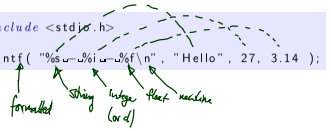
Allocate and copy: (not C99, but POSIX)

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

Input/Output

Printing

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



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.
- %

Zoom In: Preprocessing, Compiling, Linking

```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 -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);
}

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


Modules

```c
#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

Modules

```c
#include <stdio.h>

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

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

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

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();
}
```

Split into:

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

Modules At Work

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();
}
```

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.

g.h

```
#ifndef G_H
#define G_H

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

f.h

```
#ifndef F_H
#define F_H

extern int
  f();
#endif
```

g.c

```
#include "g.h"

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

f.c

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

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

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

link:

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

execute:

- % ./a.out
- Hello World.

fix and re-build:

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

g.h

```
#ifndef G_H
#define G_H

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

f.h

```
#ifndef F_H
#define F_H

extern int
  f();
#endif
```

g.c

```
#include "g.h"

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

f.c

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

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

helloworld.c

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

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


Preprocessing

helloworld.c

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

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

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

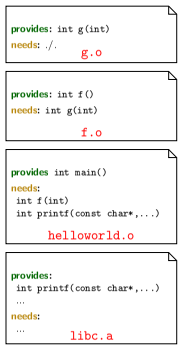
helloworld.i

```
# 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();
}
```

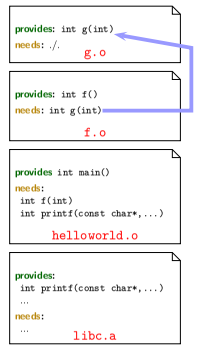

Preprocessing Directives (6.10)

```
#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;
```

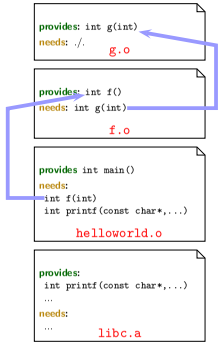

Linking



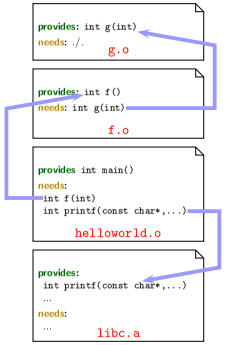
Linking



Linking



Linking



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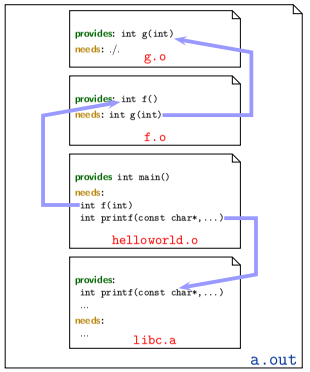


Compiler

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 `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`

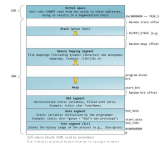
- **Build Utility**:

  `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

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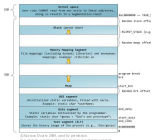

```c
int main() {
  int *p;
  *p = 27;
  return 0;
}
```

```
% 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 11, Segmentation fault.
#0 0x0000000000404b4a 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 );
```


Diagnostics (7.2)

```c
#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."

Diagnostics (7.2)

```c
#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."

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

Dependability

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

Dependability

- "**The program has been verified.**" tells us **not very much**.
- One wants to know (and should state):

Dependability

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

Dependability

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- One wants to know (and should state):
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    - Platform assumptions: finite words (size?), mathematical integers, ...
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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

Distinguish

Most **generic errors** boil down to:

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

Conformance (4)

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

  shall be a correct program and act in accordance with 5.1.2.3. (Program Execution)
- A conforming program is one that is acceptable to a conforming implementation.
- Strictly conforming programs are intended to be maximally portable among conforming implementations.
- An implementation [of C, a compiler] shall be accompanied by a document that defines all implementation-defined and locale-specific characteristics and all extensions.

Over- and Underflows

Over- and Underflows, Casting

- Not specific to C...

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


Initialisation (6.7.8)

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- "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)

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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**."

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- etc. pp.

Null-Pointer

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

Null-Pointer

```c
int main() {
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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

```c
int main() {
  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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- **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.

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

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

References

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