Formal Methods for C

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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.
- % echo $?

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();
}
```

preprocess
compile
link

- `% gcc -E helloworld.c > helloworld.i`
- `% gcc -c 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();
}
```

Split into:

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

g.h

```c
#ifndef G_H
#define G_H

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

f.h

```c
#ifndef F_H
#define F_H

extern int
  f();
#endif
```

g.c

```c
#include "g.h"

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

f.c

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

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

helloworld.c

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

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

Modules At Work

preprocess & compile:

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

link:

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

execute:

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

g.h

```c
#ifndef G_H
#define G_H

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

f.h

```c
#ifndef F_H
#define F_H

extern int
  f();
#endif
```

g.c

```c
#include "g.h"

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

f.c

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

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

helloworld.c

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

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

Modules At Work

preprocess & compile:

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

```c
#ifndef G_H
#define G_H

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

f.h

```c
#ifndef F_H
#define F_H

extern int
  f();
#endif
```

g.c

```c
#include "g.h"

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

f.c

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

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

helloworld.c

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

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

Preprocessing

helloworld.c

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

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

preprocess

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

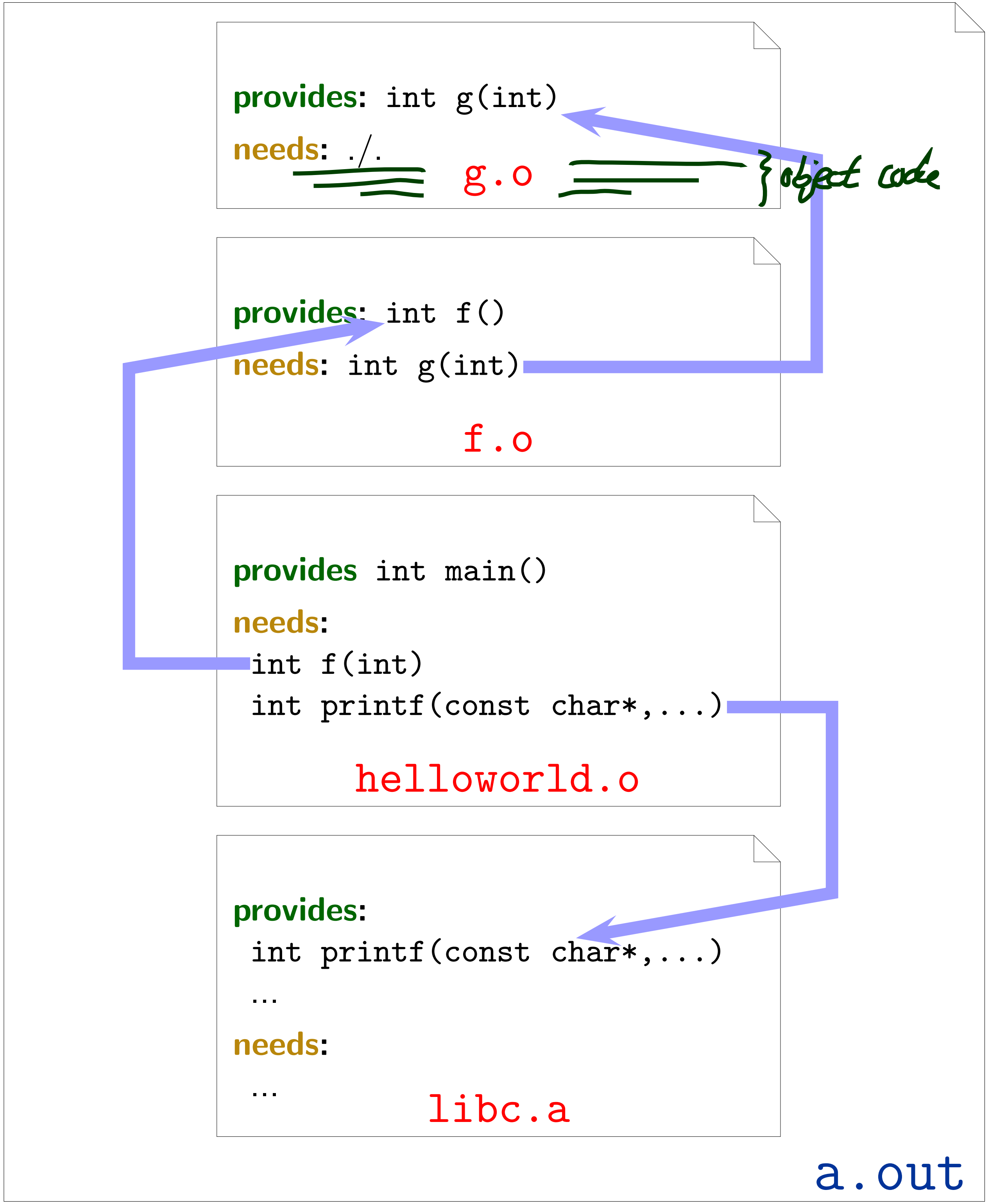
helloworld.i

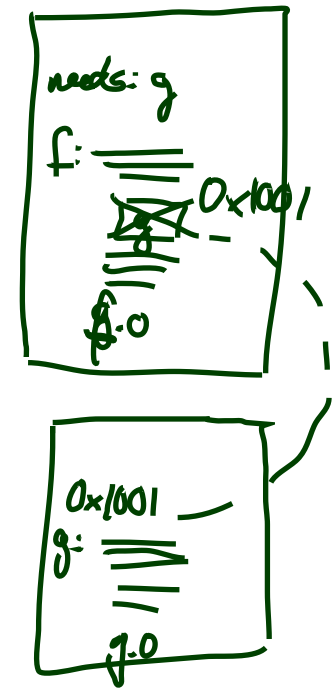
```
# 1 "helloworld.c"
# 1 "<command-line>"
# 1 "helloworld.c"
# 1 "/usr/include/stdio.h" 1 3 4
# 28 "/usr/include/stdio.h" 3 4
# 1 "/usr/include/features.h" 1 3 4
# 323 "/usr/include/features.h" 3 4
# 1 "/usr/include/x86_64-linux-gnu/bits/predefs.h" 1 3 4
# 324 "/usr/include/features.h" 2 3 4
# 356 "/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)

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

#define PI 3.1415

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

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

extern int f() __pure;
```

Linking


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


needs: g
f:
0x1001
f.o
0x1001
g:
g.o

Compiler

gcc [OPTION]... infile...

-E – preprocess only

-c – compile only, don't link

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

-o outfile – write output to **outfile**

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

-g – add debug information

-W, -Wall, ... – enable warnings

-I dir – add **dir** to **include path** for searching headers

-L dir – add **dir** to **library path** for searching libraries

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

Example: `gcc -DDEBUG -DMAGICNUMBER=27`

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

(static) (dynamic)

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**:

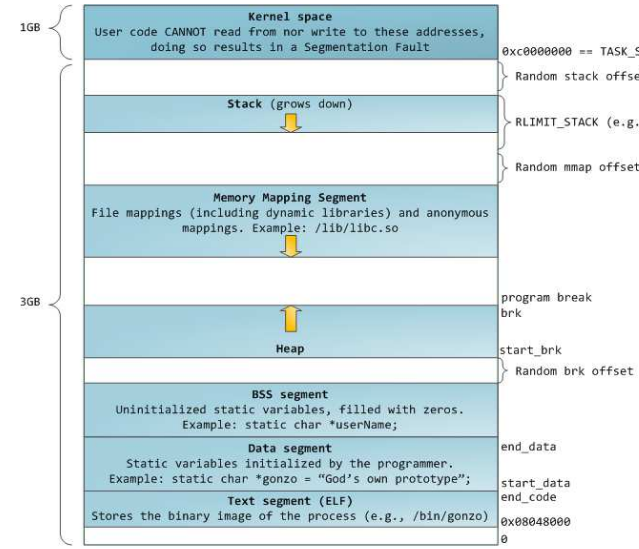
```
nm a.o
```

- **Build Utility**:

```
make
```

See battery controller exercise for an example.

Core Dumps



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

- **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 11, Segmentation fault.
#0  0x00000000004004b4 in main () at core.c:3
3          *p = 27;
(gdb) p p
$1 = (int *) 0x0
(gdb) q
```

Formal Methods for C

Correctness and Requirements

Correctness

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

Examples:

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

Common Patterns

- **State Invariants**:
  "at **this** program point, the value of p must not be NULL"
  "at **all** program points, the value of p must not be NULL"
  (cf. **sequence points** (Annex C))

- **Data Invariants**:
  "the value of n must be the length of s"

- **(Function) Pre/Post Conditions**:
  Pre-Condition: the parameter must not be 0
  Post-Condition: the return value is 10 divided by the parameter

- **Loop Invariants**:
  "the value of i is between 0 and array length minus 1"

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

Diagnostics (7.2)

```
#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>

```
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**>

```
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**>

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

  int r = 10/x;

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

  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

```
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 **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**"!
  - 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)

↖ the compiler

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

Over- and Underflows

Over- and Underflows, Casting

- Not specific to C...

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

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

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


int e = 0;

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

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

Initialisation (6.7.8)

Initialisation (6.7.8)

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

```
void f() {
  int a;

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

Unspecified Behaviour (J.1)

Unspecified Behaviour (J.1)

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

For example

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

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

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

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

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

Undefined Behaviour (J.2)

Undefined Behaviour (3.4.3)

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

"**Possible undefined behaviour ranges from**

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

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

Undefined Behaviour (J.2)

More examples:

- an identifier [...] contains an invalid multibyte character (5.2.1.2)
- an object is referred to outside of its lifetime (6.2.4)
- the value of a pointer to an object whole lifetime has ended is used (6.2.4)
- conversion to or from an integer type produces a value outside the range that can be represented (6.3.1.4)
- conversion between two pointer types produces a result that is incorrectly aligned (6.3.2.3)
- the program attempts to modify a string literal (6.4.5)
- an exceptional condition occurs during the evaluation of an expression (6.5)
- the value of the second operand of the / or % operator is zero (6.5.5)
- pointers that do not point into, or just beyond, the same array object are subtracted (6.5.6)
- An array subscript is out of range [...] (6.5.6)
- the program removes the definition of a macro whose name begins with an underscore and either an uppercase letter or another underscore (7.1.3)
- etc. pp.

Null-Pointer

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

- "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

```
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.

- 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)

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:"

- J.3.2 Environment, e.g.
  The set of signals, their semantics, and their default handling (7.14).
- J.3.3 Identifiers, e.g.
  The number of significant initial characters in an identifier (5.2.4.1, 6.4.2).
- J.3.4 Characters, e.g.
  The number of bits in a byte (3.6).
- J.3.5 Integers, e.g.
  Any extended integer types that exist in the implementation (6.2.5).
- J.3.6 Floating Point, e.g.
  The accuracy of the floating-point operations [...] (5.2.4.2.2).
- J.3.7 Arrays and Pointers, e.g.
  The result of converting a pointer to an integer or vice versa (6.3.2.3).
- etc. pp.

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

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

References

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