Testing and Debugging

Programming for Engineers
Winter 2015

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The Problem

Alan Turing

1936 schließlich führte Turing die Begriffe des Algorithmus und der Berechenbarkeit fassbar, indem er mit seinem Modell die Begriffe des Algorithmus und der Berechenbarkeit als formale, mathematische Begriffe definierte.

Halting Problem

- Not all problems can be solved by programs
- E.g. the halting problem states that there is no program which can decide for an arbitrary program *P*, whether it will (eventually) return a result or not.

Collatz Conjecture

(Lothar Collatz, 1937)

- Start with an integer *n*
- If *n* is even, take *n*/2 next
- If *n* is odd, take 3*n*+1next
- repeat

19, 58, 29, 88, 44, 22, 11, 34, 17, 52, 26,
13, 40, 20, 10, 5, 16, 8, 4, 2, 1, …

Collatz Conjecture

(Lothar Collatz, 1937)

- Apparently every sequence defined in this manner ends in 4, 2, 1, …
- This property remains unproven

19, 58, 29, 88, 44, 22, 11, 34, 17, 52, 26,
13, 40, 20, 10, 5, 16, 8, 4, 2, 1, …

Halting Problem

```
void collatz(int n) {
  while (n != 1) {
    if (n % 2 == 0)
      n = n / 2;
    else
      n = 3 * n + 1;
  }
}
```

- Will collatz() return for every n?
- Solution only by trial (in infinite time)

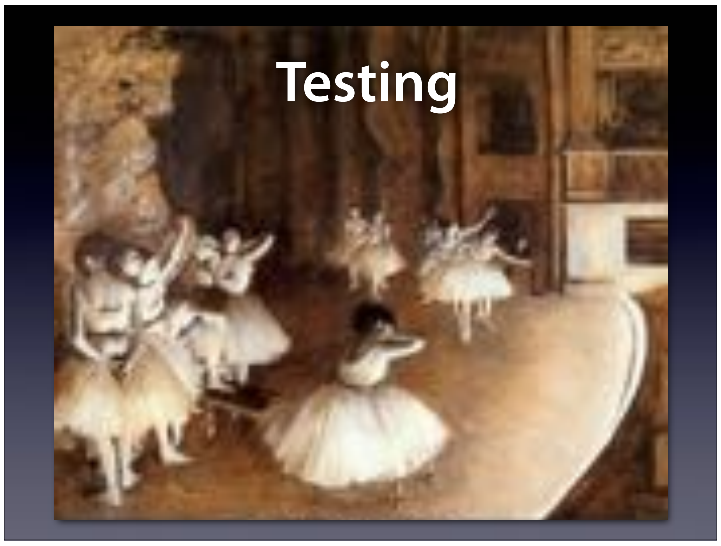
It is impossible to show correctness automatically for all programs

Halting Problem

To show that a real program fulfils its requirements, we must either

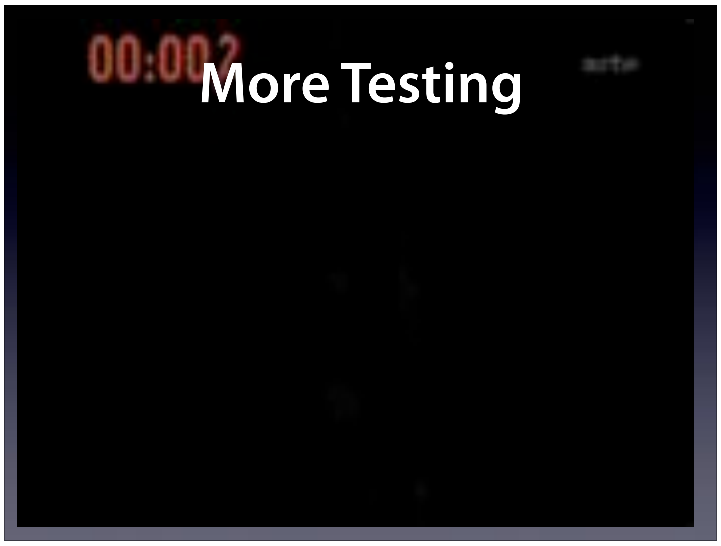
- use mathematical knowledge and assumptions to prove it by hand (which is very hard), or
- we must test it and hope that our tests suffice.

Testing



Testing

Edgar Degas: The Rehearsal. With a rehearsal, we want to check whether everything will work as expected. This is a test.



More Testing

Again, a test. We test whether we can evacuate 500 people from an Airbus A380 in 90 seconds. This is a test.

Even More Testing

And: We test whether a concrete wall (say, for a nuclear reactor) withstands a plane crash at 900 km/h. Indeed, it does.

Software is Diverse

We can also test software this way. But software is not a planned linear show – it has a multitude of possibilities. So: if it works once, will it work again? This is the central issue of testing – and of any verification method.

Software is Diverse

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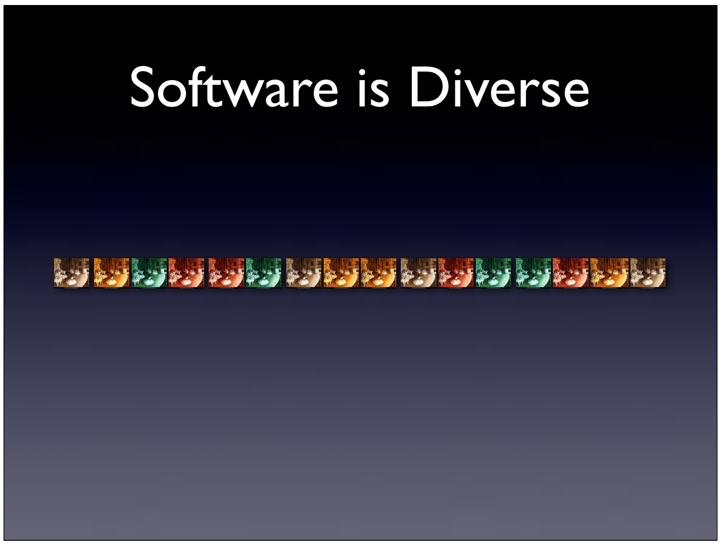
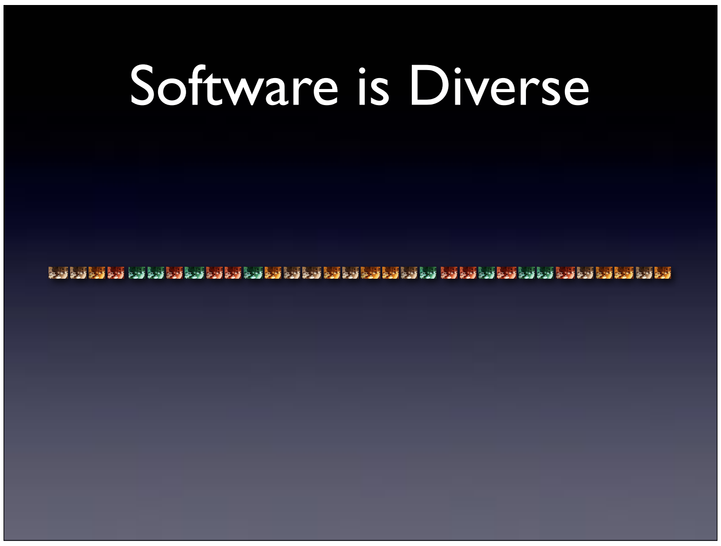
Software is Diverse

The problem is: There are many possible executions. And as the number grows…



Software is Diverse

and grows…

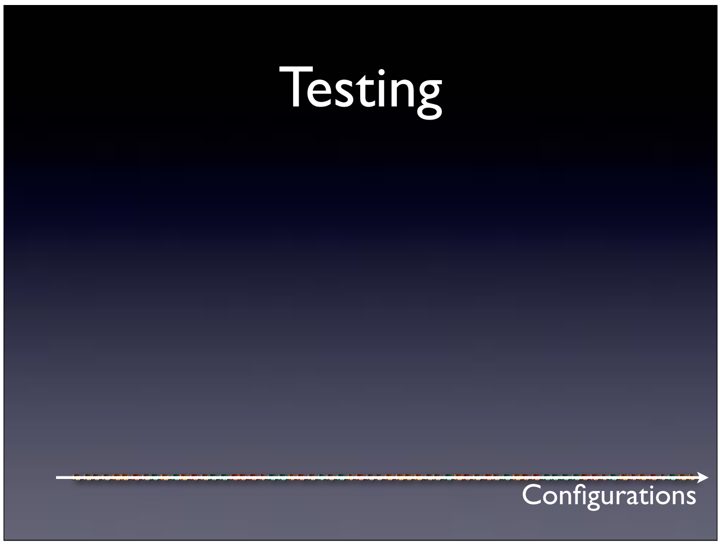


Software is Diverse

and grows…

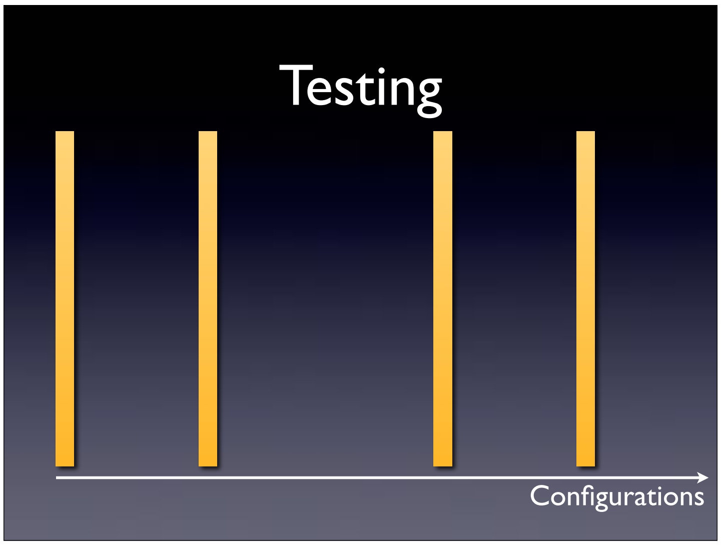
Software is Diverse

and grows…



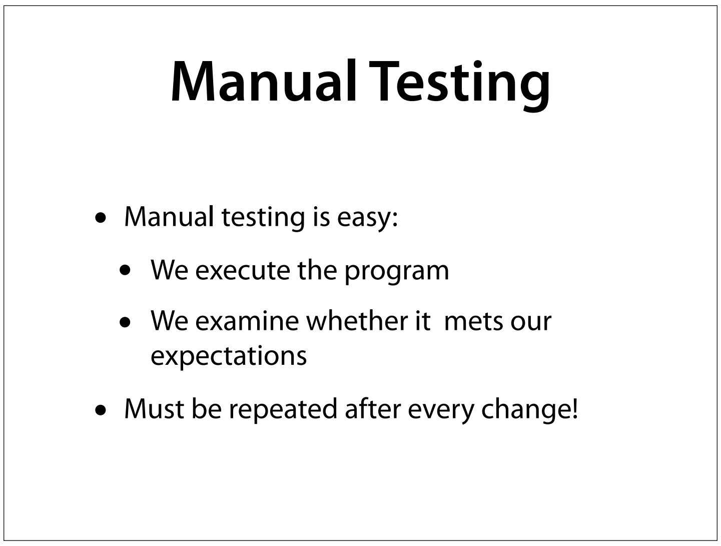
Testing

…you get an infinite number of possible executions, but you can only conduct a finite number of tests.



Testing

With testing, you pick a few of these Konfigurationens – and test them.



Manual Testing

- Manual testing is easy:
  - We execute the program
  - We examine whether it mets our expectations
- Must be repeated after every change!

Automatic Testing

- A special test function checks another function for correctness:

```
void test_sqrt() {
  if (sqrt(4) != 2)
    error();
  if (sqrt(9) != 3)
    error();
  if (sqrt(16) != 4)
    error();
}
```

- After every change: simply re-execute the tests

Assertions

- In order to ensure a condition, programs use assertions
- assert(*p*) fails if p does not hold

```
#include <assert.h>

void test_sqrt() {
  assert(sqrt(4) == 2);
  assert(sqrt(9) == 3);
  assert(sqrt(16) == 4);
}
```

Diagnosis

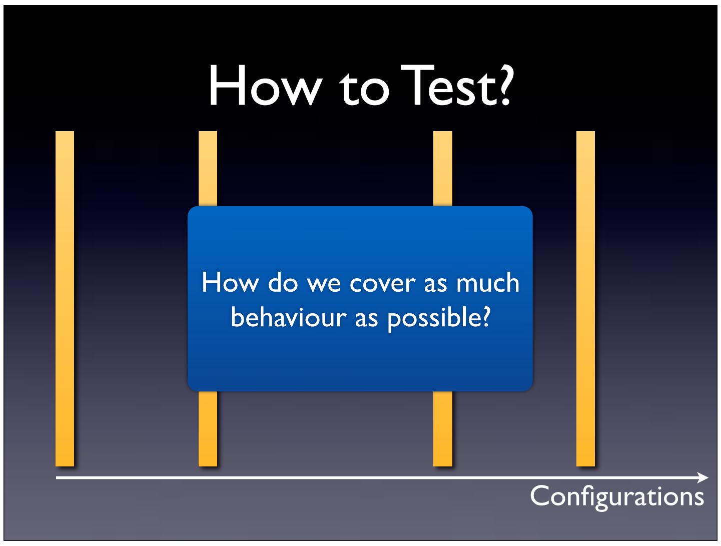
- Usually assert(*p*) halts the program directly (“abort()”)
- If defined, the function __assert() is called instead, which prints additional information.
- Especially useful on Arduino

Diagnosis

```
#define __ASSERT_USE_STDERR
#include <assert.h>

void __assert(const char *failedexpr,
              const char *file,
              int line,
              const char *func)
{
     Serial.print(file);
     Serial.print(":");
     Serial.print(line);
     Serial.print(": ");
     Serial.print(func);
     Serial.print(": Assertion failed: ");
     Serial.println(failedexpr);
     abort();
}
```

```
Assert.ino:20: setup(): Assertion failed: 2 + 2 == 5
```

How to Test?



So, how can we cover as much behavior as possible?

What to Test?

- Goal: Cover every aspect of the behaviour
- Required behaviour: by specification *(functional testing)*
- Implemented behaviour: by *code* *(structural testing)*

Functional Testing

- *cgi_decode* takes a string and

1. replaces every "+" with a space
2. replaces every "%*xx*" with a character with hexadecimal value *xx*
   (returns an error code if *xx is invalid*)
3. All other characters remain unchanged

- These properties must be tested!

Functional Testing

```c
#include <assert.h>

// replaces every "+" with a space
void test_cgi_decode_plus() {
  char *encoded = "foo+bar+";
  char decoded[20];

  int result = cgi_decode(encoded, decoded);
  assert(result == 0);
  assert(strcmp(decoded, "foo bar ") == 0);
}
```

Functional Testing

```c
#include <assert.h>

// replaces every "%xx"
// with a character with hexadecimal value xx
void test_cgi_decode_hex() {
  char *encoded = "foo%30bar";
  char decoded[20];

  int result = cgi_decode(encoded, decoded);
  assert(result == 0);
  assert(strcmp(decoded, "foo0bar") == 0);
}
```

Functional Testing

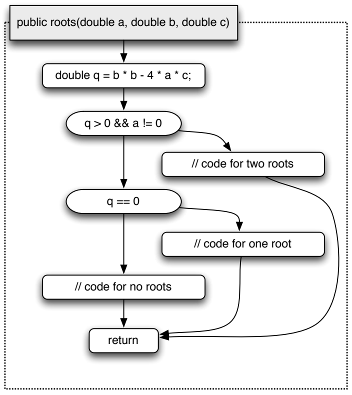
```
#include <assert.h>

// replaces every "%xx"
// with a character with hexadecimal value xx
void test_cgi_decode_invalid_hex() {
  char *encoded = "foo%zzbar";
  char decoded[20];

  int result = cgi_decode(encoded, decoded);
  assert(result != 0);
}
```

Test Suite

- A *test suite* combines multiple tests
- Execute after every change

```
#include <assert.h>

// All tests
void test_cgi_decode() {
   test_cgi_decode_plus();
   test_cgi_decode_hex();
   test_cgi_decode_invalid_hex();
}
```

Structural Testing



- Based on the *structure* of the *program*
- The more parts of the program are *covered* (executed), the higher the chance to find errors
- "Parts" can be: instructions, transition, paths, conditions…

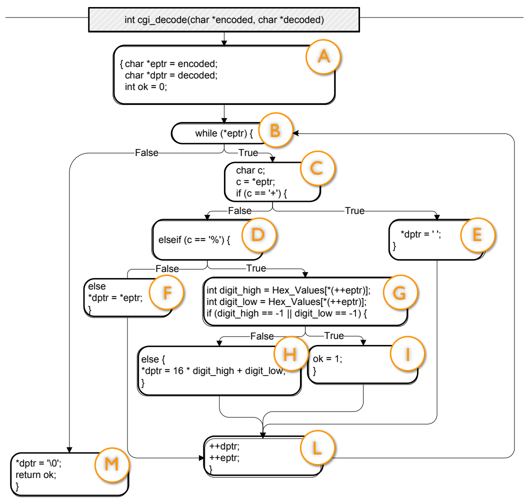
To talk about structure, we turn the program into a *control flow graph*, where statements are represented as nodes, and edges show the possible control flow between statements.

cgi_decode

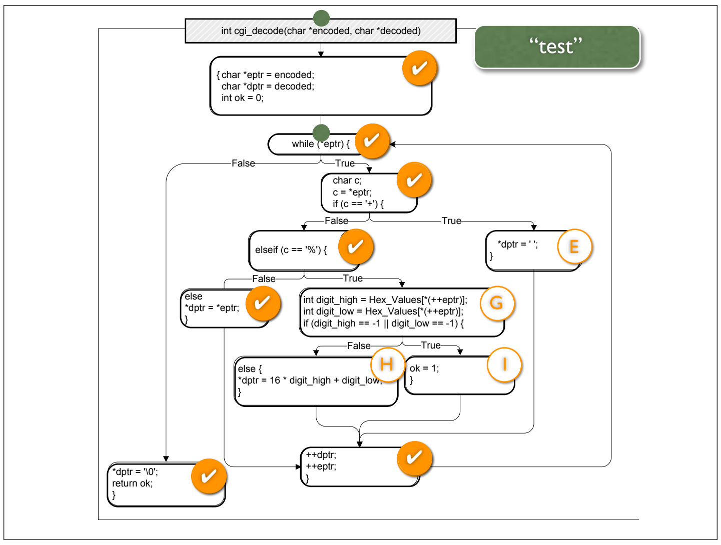
```
/**
  * @title cgi_decode
  * @desc
  * Translate a string from the CGI encoding to plain ascii text
  * '+' becomes space, %xx becomes byte with hex value xx,
  * other alphanumeric characters map to themselves
  *
  * returns 0 for success, positive for erroneous input
  * 1 = bad hexadecimal digit
  */

int cgi_decode(char *encoded, char *decoded)
{
    char *eptr = encoded;
    char *dptr = decoded;  A
    int ok = 0;
```

Here's an ongoing example. The function cgi_decode translates a CGI-encoded string (i.e., from a Web form) to a plain ASCII string, reversing the encoding applied by the common gateway interface (CGI) on common Web servers.
(from Pezze + Young, "Software Testing and Analysis", Chapter 12)

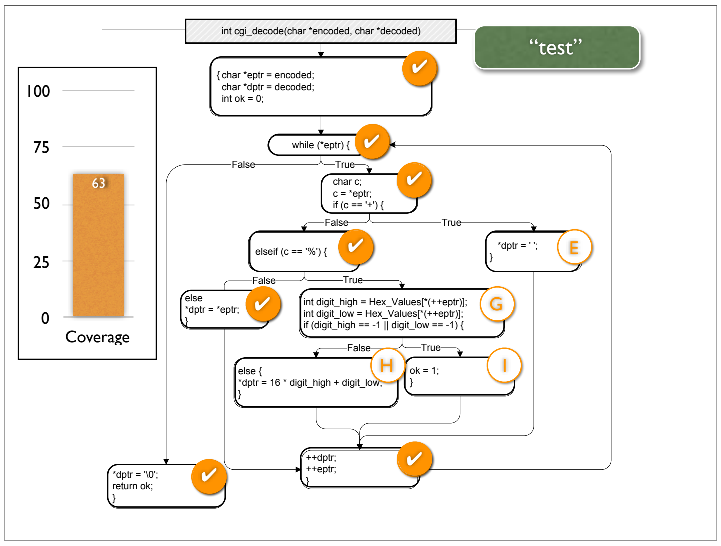
```
    while (*eptr)  /* loop to end of string ('\0' character) */  B
    {
        char c;
        c = *eptr;  C
        if (c == '+') {  /* '+' maps to blank */
            *dptr = ' ';  E
        } else if (c == '%') { /* '%xx' is hex for char xx */  D
            int digit_high = Hex_Values[*(++eptr)];
            int digit_low  = Hex_Values[*(++eptr)];  G
            if (digit_high == -1 || digit_low == -1)
                ok = 1; /* Bad return code */  I
            else
                *dptr = 16 * digit_high + digit_low;  H
        } else { /* All other characters map to themselves */
           *dptr = *eptr;  F
        }
        ++dptr; ++eptr;  L
    }

    *dptr = '\0';   /* Null terminator for string */  M
    return ok;
}
```


int cgi_decode(char *encoded, char *decoded)
{ char *eptr = encoded; char *dptr = decoded; int ok = 0;
A
while (*eptr) {
B
False
True
char c; c = *eptr; if (c == '+') {
C
False
True
elseif (c == '%') {
D
*dptr = ' '; }
E
False
True
else *dptr = *eptr; }
F
int digit_high = Hex_Values[*(++eptr)]; int digit_low = Hex_Values[*(++eptr)]; if (digit_high == -1 || digit_low == -1) {
G
False
True
else { *dptr = 16 * digit_high + digit_low; }
H
ok = 1; }
I
++dptr; ++eptr; }
L
*dptr = '\0'; return ok; }
M

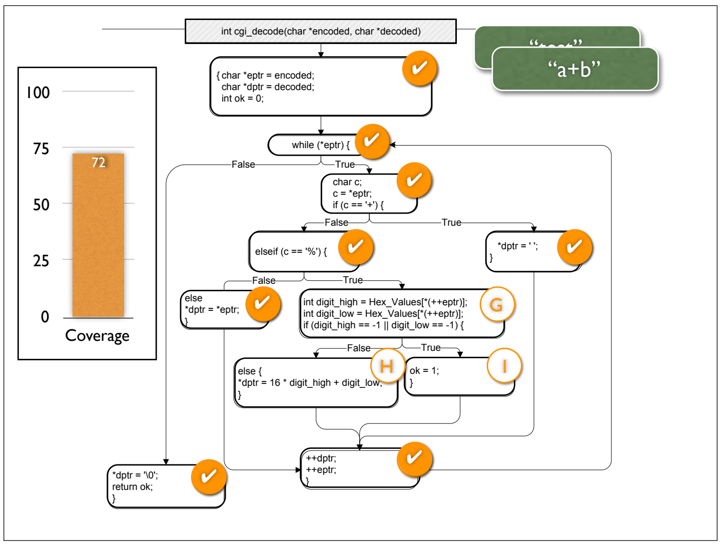
This is what cgi_decode looks as a CFG.
(from Pezze + Young, "Software Testing and Analysis", Chapter 12)



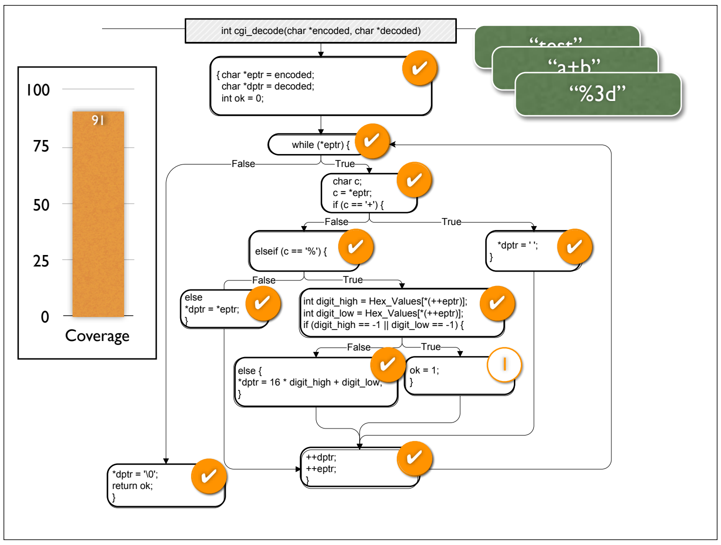
While the program is executed, one statement (or basic block) after the other is covered – i.e., executed at least once – but not all of them. Here, the input is "test"; checkmarks indicate executed blocks.



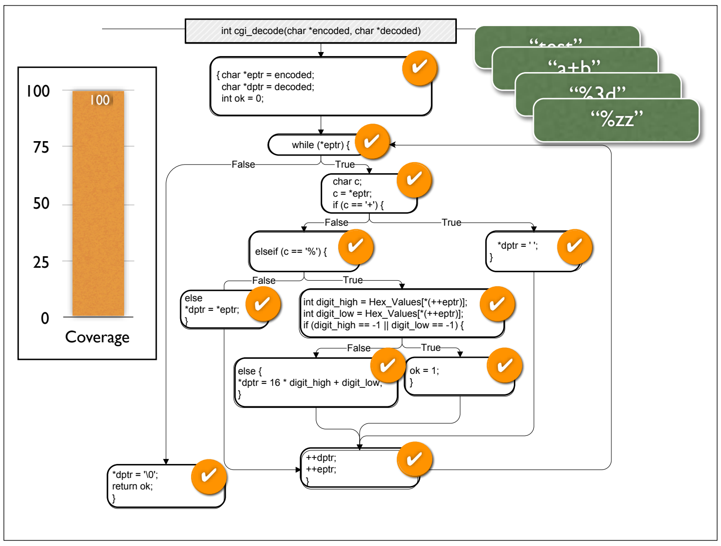
The initial Coverage is 7/11 blocks = 63%. We could also count the statements instead (here: 14/20 = 70%), but conceptually, this makes no difference.



and the Coverage increases with each additionally executed statement…



int cgi_decode(char *encoded, char *decoded)
{ char *eptr = encoded; char *dptr = decoded; int ok = 0;
while (*eptr) {
False
True
char c; c = *eptr; if (c == '+') {
elseif (c == '%') {
*dptr = ' '; }
else *dptr = *eptr; }
int digit_high = Hex_Values[*(++eptr)]; int digit_low = Hex_Values[*(++eptr)]; if (digit_high == -1 || digit_low == -1) {
else { *dptr = 16 * digit_high + digit_low; }
ok = 1; }
++dptr; ++eptr; }
*dptr = '\0'; return ok; }
100
75
50
25
0
91
Coverage
"test"
"a+b"
"%3d"



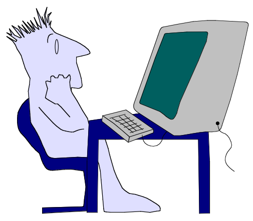
int cgi_decode(char *encoded, char *decoded)
{ char *eptr = encoded; char *dptr = decoded; int ok = 0;
while (*eptr) {
False
True
char c; c = *eptr; if (c == '+') {
elseif (c == '%') {
*dptr = ' '; }
else *dptr = *eptr; }
int digit_high = Hex_Values[*(++eptr)]; int digit_low = Hex_Values[*(++eptr)]; if (digit_high == -1 || digit_low == -1) {
else { *dptr = 16 * digit_high + digit_low; }
ok = 1; }
++dptr; ++eptr; }
*dptr = '\0'; return ok; }
100
75
50
25
0
100
Coverage
"test"
"a+b"
"%3d"
"%zz"

… until we reach 100% block Coverage (which is 100% statement Coverage, too).

A Test…

- should not show that a program works
- but rather show that a program does not work
- requires creativity in testing!

Who Should Test?



Developer

- *understands* the system
- will test *cautiously*
- wants to deliver *code*

Independent Tester

- must *learn* the system
- wants to uncover *errors*
- wants to deliver *quality*

From Pressman, “Software Engineering – a practitioner’s approach”, Chapter 13

The Best Tester

A good tester should be creative and destructive – even sadistic in places.
– Gerald Weinberg, “The psychology of computer programming”

The Developer

The conflict between developers and testers is usually overstated, though.

Weinberg’s Law

A developer is not suited to test their own code.

Theory: As humans want to be honest with themselves, developers are blindfolded with respect to their own mistakes.
Evidence: “seen again and again in every project” (Endres/Rombach)
From Gerald Weinberg, “The psychology of computer programming”

Sadistic Test

```c
#include <assert.h>

// replaces every “%xx”
// with a character with hexadecimal value xx
void test_cgi_decode_incomplete_hex() {
  char *encoded = "foo%g";
  char decoded[20];

  int result = cgi_decode(encoded, decoded);
  assert(result != 0);
}
```

- Leads to access outside array bounds

Debugging

- Testing is followed by debugging

Nach dem Testing folgt die Fehlersuche

Systematic Debugging

Track the problem
Reproduce
Automate
F ind Origins
F ocus
I solate
Correct

T
R
A
F
F
I
C

Tracking the Problem

trac

(9) Time Tracking

T
R
A
F
F
I
C

Tracking the Problem

- Every problem is entered into the bug database
- The priority determines what problem will be addressed next
- When all problems are solved, the product is finished

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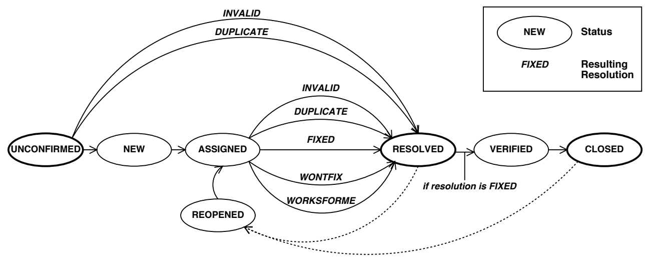
Life Cycle of a Problem



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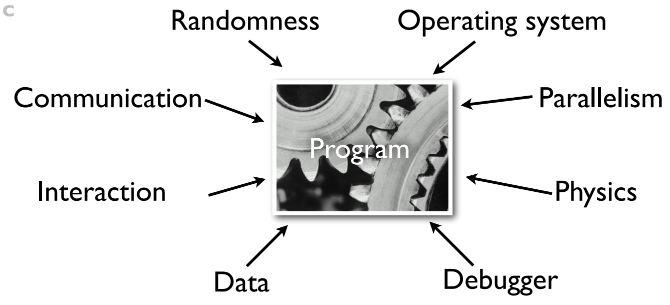
Reproducing



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Automating

```
// Test for host
public void testHost() {
  int noPort = -1;
  assertEquals(askigor_url.getHost(), "www.askigor.org");
  assertEquals(askigor_url.getPort(), noPort);
}

// Test for path
public void testPath() {
  assertEquals(askigor_url.getPath(), "/status.php");
}

// Test for query part
public void testQuery() {
  assertEquals(askigor_url.getQuery(), "id=sample");
}
```

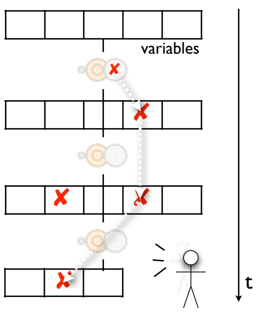
Automating

- Every problem should be automatically reproducible
- This is done by means of unit tests
- The test cases are executed after every change

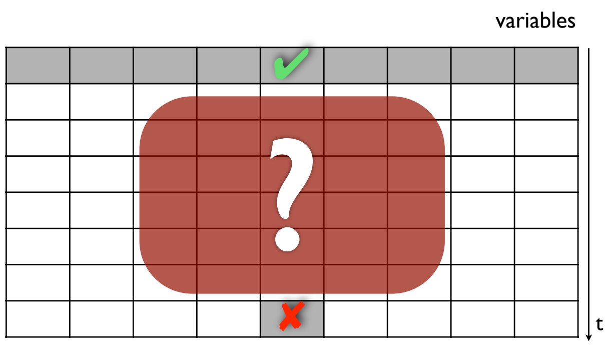
Finding the Origin

1. The programmer creates a *defect* – an error in the code
2. The executed defect creates an *infection* – an error in the program state
3. The infection spreads…
4. …and becomes visible as a *malfunction*.

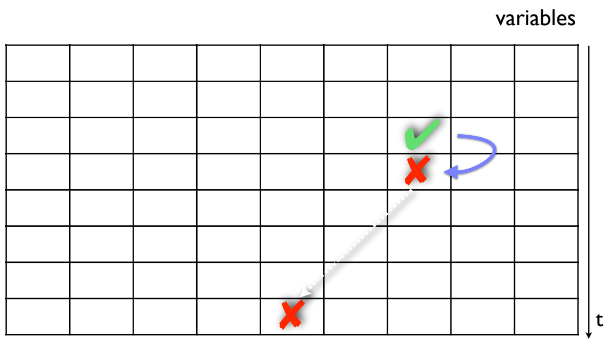
We must *break* this infection chain.



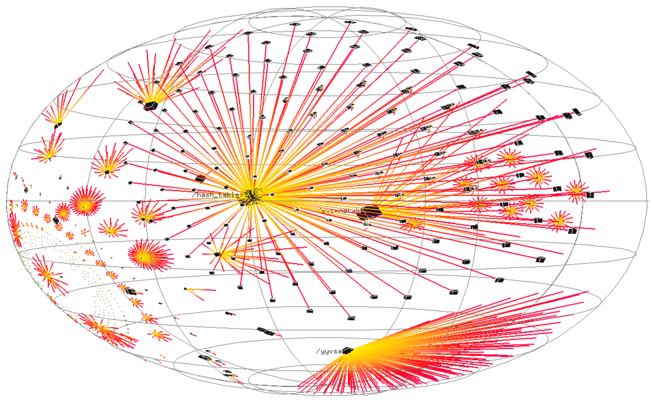
Finding the Origin



The Defect



A Program State



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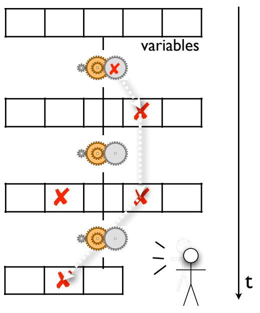
Finding the Origin

1. We start with a *known infection* (e.g. at the end of the *execution*)
2. We look for the infection in the *previous* state



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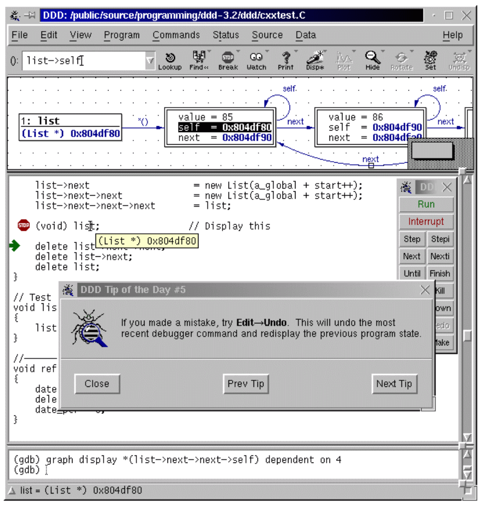

```
1: list
(List *) 0x804df80

value = 85
self  = 0x804df80
next  = 0x804df90

value = 86
self  = 0x804df90
next  = 0x804df
```

```
    list->next                     = new List(a_global + start++);
    list->next->next               = new List(a_global + start++);
    list->next->next->next         = list;

    (void) list;                   // Display this

    delete list
    delete list->next;
    delete list;
}

// Test
void lis
{
    list
}

//
void ref
{
    date
    dele
    date
}
```

(List *) 0x804df80

If you made a mistake, try **Edit→Undo**. This will undo the most recent debugger command and redisplay the previous program state.

```
(gdb) graph display *(list->next->next->self) dependent on 4
(gdb)
```

list = (List *) 0x804df80

T
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A
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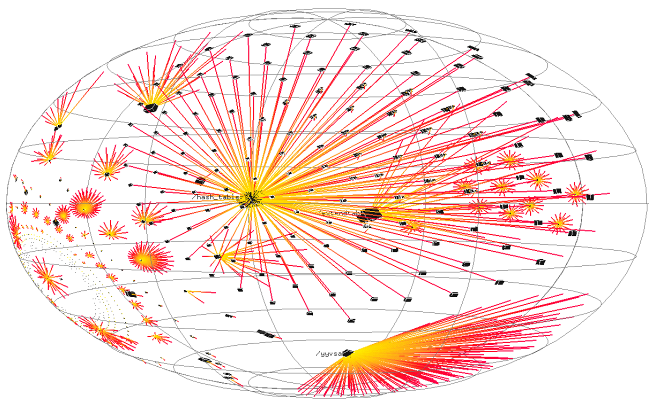
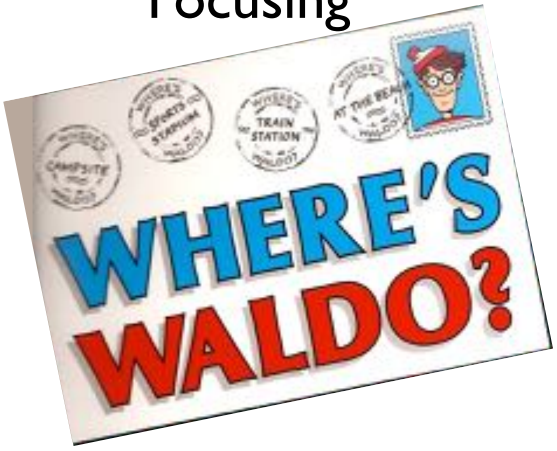
F
I
C

A Program State



Focusing



Focusing

When searching for infections, we focus on places in the program state, that are

- *probably wrong* (e.g. because there were errors here previously)
- *explicitly wrong* (e.g. because they fail an assertion)

Assertions are the most effective means for finding infections.

Finding Infections

```
struct Time {
    int hour;     // 0..23
    int minutes;  // 0..59
    int seconds;  // 0..60 (incl. leap seconds)
};

void set_hour(struct Time *t, int h);
…
```

Every value from 00:00:00 to 23:59:60 is valid

Finding the Origin

```
int sane_time(struct time *t)
{
    return (0 <= t->hour && t->hour <= 23) &&
           (0 <= t->minutes && t->minutes <= 59) &&
           (0 <= t->seconds && t->seconds <= 60);
}

void set_hour(struct Time *t, int h)
{
    assert (sane_time(t));  // Precondition
    …
    assert (sane_time(t));  // Postcondition
}
```

Finding the Origin

```
int sane_time(struct time *t)
{
    return (0 <= t->hour && t->hour <= 23) &&
           (0 <= t->minutes && t->minutes <= 59) &&
           (0 <= t->seconds && t->seconds <= 60);
}
```

sane() is the *invariant* of a time object:

- holds *before* every time function
- holds *after* every time function

Finding the Origin

- Precondition fails = infection *before* the function
- Postcondition fails = infection *in* the function itself
- All assertions ok = no infection

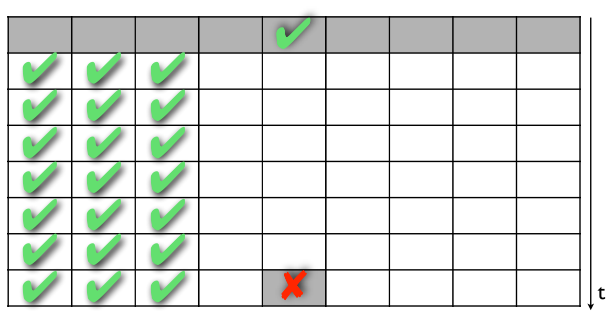
```
void set_hour(struct Time *t, int h)
{
    assert (sane_time(t));  // precondition
    …
    assert (sane_time(t));  // postcondition
}
```

Complex Invariants

```
int sane_tree(struct Tree *t) {
      assert (rootHasNoParent(t));
      assert (rootIsBlack(t));
      assert (redNodesHaveOnlyBlackChildren(t));
      assert (equalNumberOfBlackNodesOnSubtrees(t));
      assert (treeIsAcyclic(t));
      assert (parentsAreConsistent(t));

      return 1;
  }
}
```

Assertions



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Focusing

- All possible influences must be checked
- Focusing on most likely candidates
- Assertions help to find infections fast

T
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C

Isolating

- Error causes are narrowed down *systematically* – using observations and experiments.

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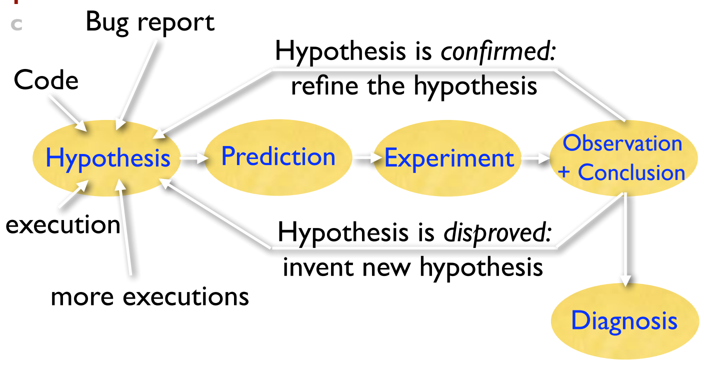
The Scientific Method

1. Observe a part of the universe
2. Formulate a *hypothesis* that is consistent with the observation
3. Use the hypothesis to make predictions.
4. Test the predictions using experiments or observations and adapt the hypothesis.
5. Repeat 3 and 4 until the hypothesis becomes a theory.

The Scientific Method



Explicit Hypotheses

Hypothesis	The execution causes a[0] = 0
Prediction	At l[illegible] should hold.
Experime[illegible]	[illegible]7.
Observati[illegible]	[illegible]as predicted.
Conclusion	Hypothesis is **confirmed**.

Remembering everything is like playing Mastermind with your eyes closed!

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Explicit Hypotheses

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Isolating

- We repeat the search for infection origins until we find the defect.
- We proceed *systematically* — in terms of the scientific method
- We guide the search through *explicit* steps which we can retrace at any time

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Correcting

Before correcting we must ensure that the defect

- is indeed an error and
- it *causes* the malfunction

Only when both are ensured and understood, we may correct the error.

The Devil's Guide to Debugging

Find the defect by guessing:

- Spread debugging instructions everywhere
- Change the code until something works
- Don't make backups of old versions
- Don't even try to understand what the program is supposed to do

The Devil's Guide to Debugging

Don't waste time trying to get to the bottom of the problem

- Most problems are trivial anyway

The Devil's Guide to Debugging

Use the most obvious repair:

- Repair only what you see:

```
x = compute(y);
// compute(17) is wrong - fix it
if (y == 17)
    x = 25.15;
```

Why deal with compute()?

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Successful Correction

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Homework

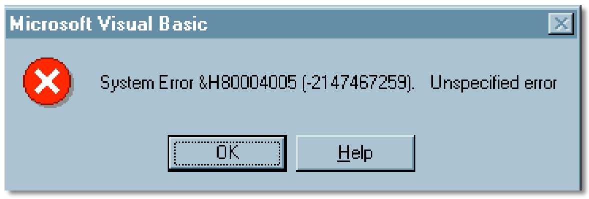
- Is the malfunction no longer present?
  (it should be a big surprise if it is still there)
- Could the correction introduce new errors?
- Was the same error made elsewhere?
- Is my correction entered into the version control system and bug tracking?

Systematic Debugging

Track the problem
Reproduce
Automate
F ind Origins
F ocus
I solate
Correct

What is a Problem?

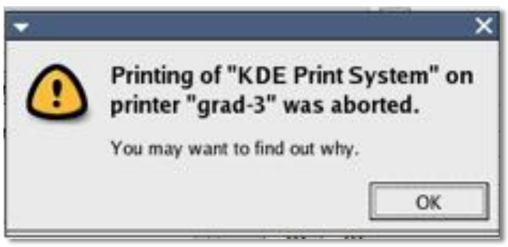
- Everything is a problem, that is perceived as such by the user
- Developers must be able to take a user perspective



Microsoft Visual Basic

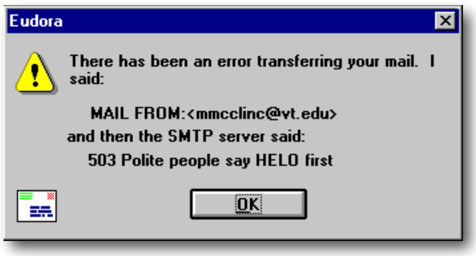
System Error &H80004005 (-2147467259). Unspecified error

Diese höchst aussagekräftige Fehlermeldung ist Microsoft Visual Basic 5.0 zu entnehmen. Nach dem Klicken auf Help erhalten wir: Visual Basic encountered an error that was generated by the system or an
external component and no other useful information was returned. The specified error number is returned by the system or external component (usually from an Application Interface call) and is displayed in hexadecimal and decimal format.
Lösung des Problems: Neu booten?



Printing of "KDE Print System" on printer "grad-3" was aborted.

You may want to find out why.

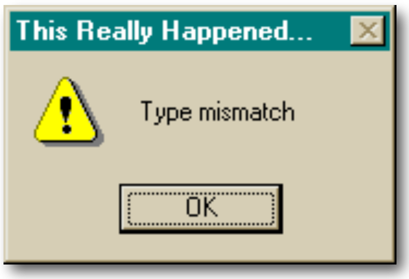

Eudora

There has been an error transferring your mail. I said:

MAIL FROM:<mmcclinc@vt.edu>

and then the SMTP server said:

503 Polite people say HELO first


This Really Happened...

Type mismatch

```
$ ssh somehost.foo.com
You don’t exist, go away!
$ _
```

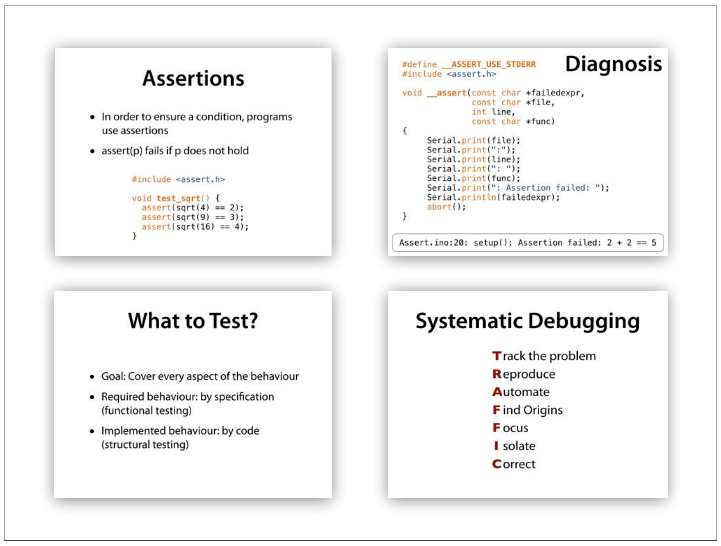
Diese Fehlermeldung erscheint etwa, wenn der NIS-Server gerade nicht erreichbar ist. Nicht, daß man den Benutzer darüber aufklären würde...

What is a Problem?

- Everything is a problem, that is perceived as such by the user
- Developers must be able to take a user perspective
- Solution: *Testing with real users!*

Task: Email A Tale of Two Cities to arthur@ximian.com; Subject14
http://www.betterdesktop.org/wiki/index.php?title=Data

Typische Vorgehensweise: Benutzer sollen mit dem System eine bestimmte Aufgabe erledigen – und halten anschließend fest, was sie gestört hat.



Assertions

- In order to ensure a condition, programs use assertions
- assert(p) fails if p does not hold

```
#include <assert.h>

void test_sqrt() {
  assert(sqrt(4) == 2);
  assert(sqrt(9) == 3);
  assert(sqrt(16) == 4);
}
```

Diagnosis

```
#define __ASSERT_USE_STDERR
#include <assert.h>

void __assert(const char *failedexpr,
              const char *file,
              int line,
              const char *func)
{
    Serial.print(file);
    Serial.print(":");
    Serial.print(line);
    Serial.print(": ");
    Serial.print(func);
    Serial.print(": Assertion failed: ");
    Serial.println(failedexpr);
    abort();
}
```

```
Assert.ino:20: setup(): Assertion failed: 2 + 2 == 5
```

What to Test?

- Goal: Cover every aspect of the behaviour
- Required behaviour: by specification (functional testing)
- Implemented behaviour: by code (structural testing)

Systematic Debugging

Track the problem
Reproduce
Automate
Find Origins
Focus
Isolate
Correct