Debugging

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(with some material by Mike Zastre)

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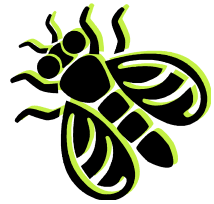
Topics

- Kinds of Programming Errors
- What is a Bug?
- Classifying Different Kinds of Bugs
- Bug Avoidance Strategies
- Bug Detection Approaches
- Debugging Tools

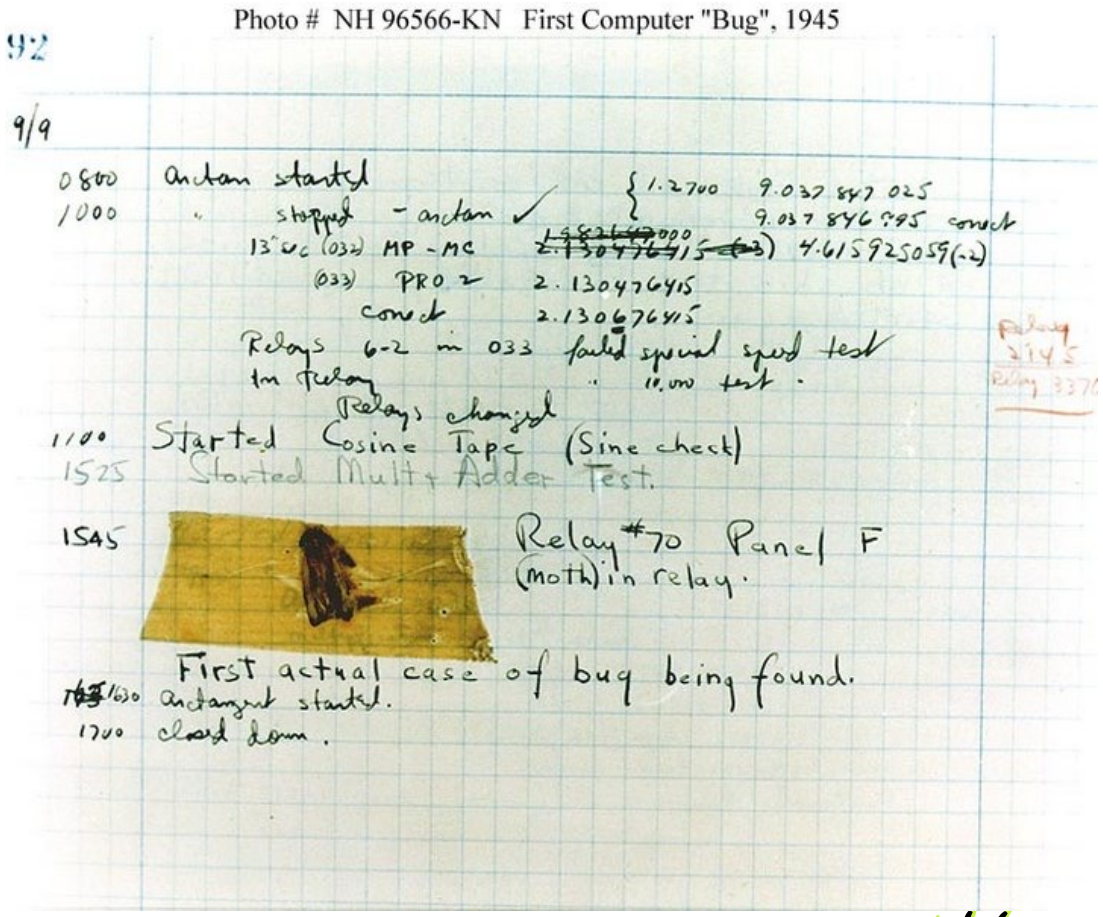


History Lesson: The First Bug?

A dead moth found trapped between electrical contacts in the **Mark II Aiken Relay Calculator**,

9 September 1945.

(Some say it was 1947.)

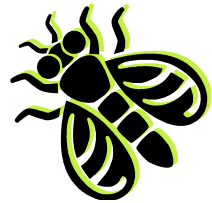


Source: Wikipedia entry for *bug*

A Bug is NOT:

any kind of mistake which causes the compiler to generate an error message

any kind of error which causes the linker to report a problem (typically an undefined or duplicate symbol).



Bug Terminology

failure	fault	error
something visible to the program's user	the state of the program which leads to a failure	the incorrect code fragment which leads to the fault and thus to the failure

Source: Andrew Ko and Brad Myers, "Development and Evaluation of a Model of Programming Errors", HCC'03.

Some Observable Failures

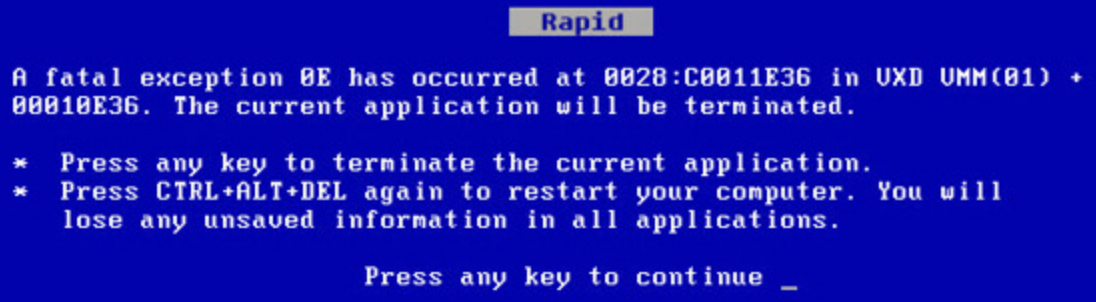
- **Infinite Loop**
- **Deadlock**
- **Incorrect Output**
- **Memory Leak**
- **Run-Time Exception**
  - the exception possibilities are very language and platform dependent

Run-Time Failure Examples

Some Possibilities for C/C++ or Assembler Code

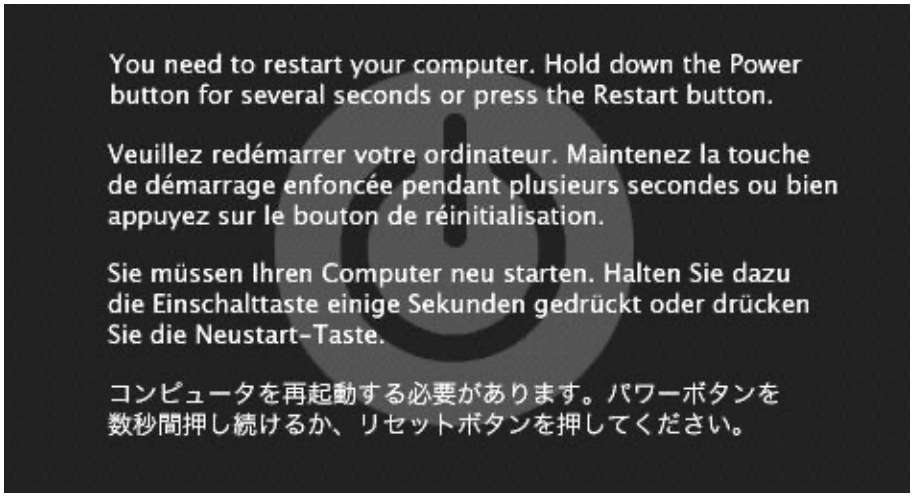
- "Blue Screen of Death"
- Segmentation fault
- Unaligned memory address
- Invalid instruction
- …

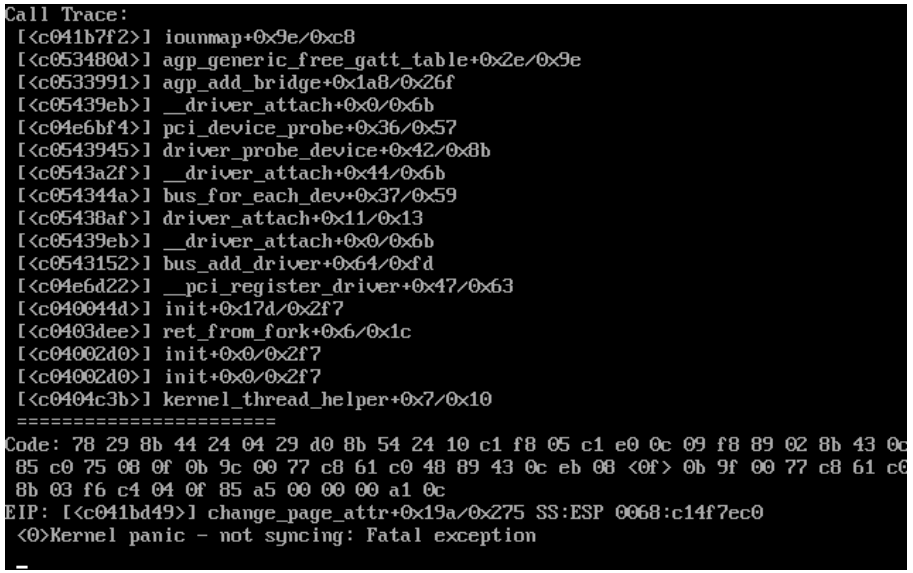
The Infamous Blue Screen of Death

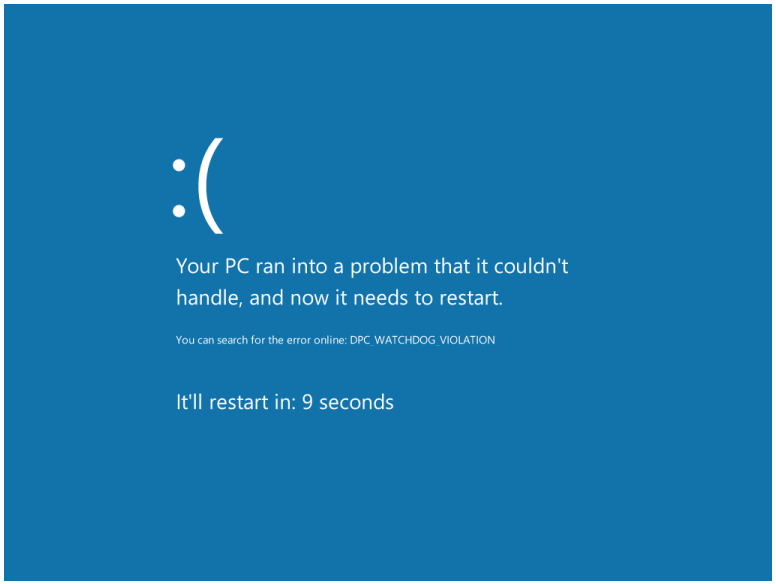


Now just a memory!

But we have new BSOD flavours







Segmentation Fault

What happens if we try to run this incorrect program?

```
% gcc segfault.c
% a.out
* i = 0
* i = 1
Segmentation Fault
   (core dumped)
%
```

```
#include <stdio.h>

int A[100];

int main() {
  int *p, i;
  p = A; i = 0;
  while(1) {
    printf("* i = %d\n",i++);
    *p = 0;
    p -= 100;
  }
  return 0;
}
```

What is a Segmentation Fault?

The program tries to access a memory location which is outside its accessible range

Typically caused by an array index which is out of range, or by an uninitialized or invalid pointer variable

The CPU generates an interrupt

The O.S. intercepts it

The O.S. kills the program

Bus Error

```
# On Intel x86
% gcc unaligned.c
% a.out
Storing 0 at address
   80608A1
%
```

```
# On PowerPC
% gcc unaligned.c
% a.out
Storing 0 at address 20901
Bus Error
%
```

```
/* C code example */
#include <stdio.h>
int A[100];

int main() {
  int *p, i;
  p = A;
  p = (int*)((int)A + 1);
  printf("Storing 0 at"
    " address %X\n", p);
  *p = 0;
  return 0;
}
```

What is a Bus Error?

The program has tried to access a misaligned data item

e.g. a 4-byte integer at a location which is not divisible by 4.

Typically caused by uninitialized pointers

Some computers generate an interrupt

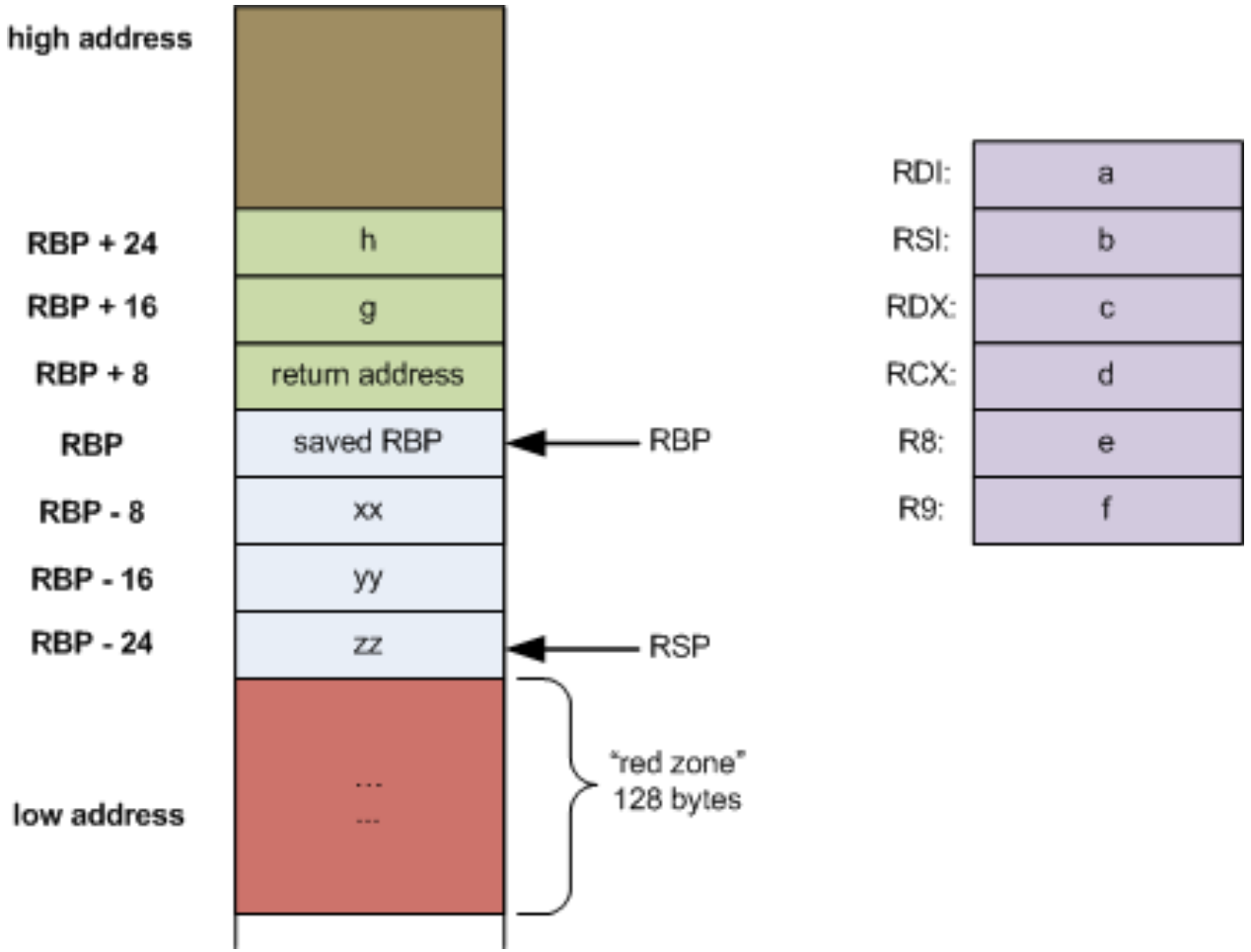
Other computers permit an unaligned data access (slowly) and continue

Illegal Instruction (sometimes)

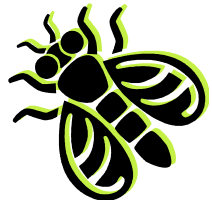
```
# On Intel x86
# But depends on version
# of gcc
% gcc badinstr.c
% a.out
In foo
Illegal instruction
   (core dumped)
%
```

```
/* C code example */
#include <stdio.h>

void foo() {
     int a, *ap;
     ap = &a;
     printf("In foo\n");
     ap[2] -= 3;
}

int main() {
     foo();
     printf("I'm back!\n");
     return 0;
}
```

(stack frame)



Source: http://eli.thegreenplace.net/2011/09/06/stack-frame-layout-on-x86-64/



How did we get to an Illegal Instruction?

The program has tried to execute an unassigned or privileged opcode

caused either by overwriting the text (instruction) area or by overwriting the return address from a subroutine – and that's usually due to a bad array index or pointer.

The CPU generates an interrupt

The O.S. intercepts it

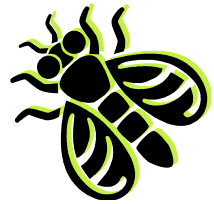
The O.S. kills the program

Memory Leak

The program runs, getting slower and slower, until some random failure occurs.

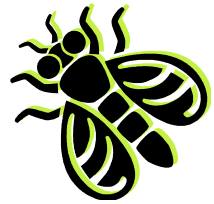
In a driver program or similar, it's the OS which gradually degrades.

```
#include <stlib.h>

void foo() {
    int *ap;
    ap = malloc(4000);
    …
    // return without
    // freeing the array
}

int main() {
    …
        foo();
    …
}
```



Avoiding Memory Leaks

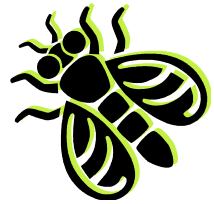
- Use a programming language where garbage collection is implicit (Java, C#, Perl, Python …)
- Otherwise, have every subroutine deallocate the objects it creates (except for objects returned as results).
- Take advantage of tools such as valgrind which probe for improper use of dynamic memory.
- And code the program very carefully!



Run-Time Failure Examples

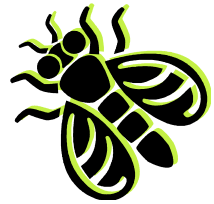
Some Possibilities for Java (or C#)

- ArithmeticException
- ArrayIndexOutOfBoundsException
- NullPointerException
- ClassCastException
- OutOfMemoryException
- … *the complete list is very long!*



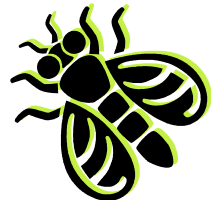
Bug Classifications

- An early and still a definitive list of bug types is due to Donald Knuth.
- He kept a logbook of 850 coding errors when developing TEX.
- He classified the errors into 15 categories.
- The list here is a condensed version due to Adam Barr. (*Find The Bug*, Addison-Wesley, 2005.)

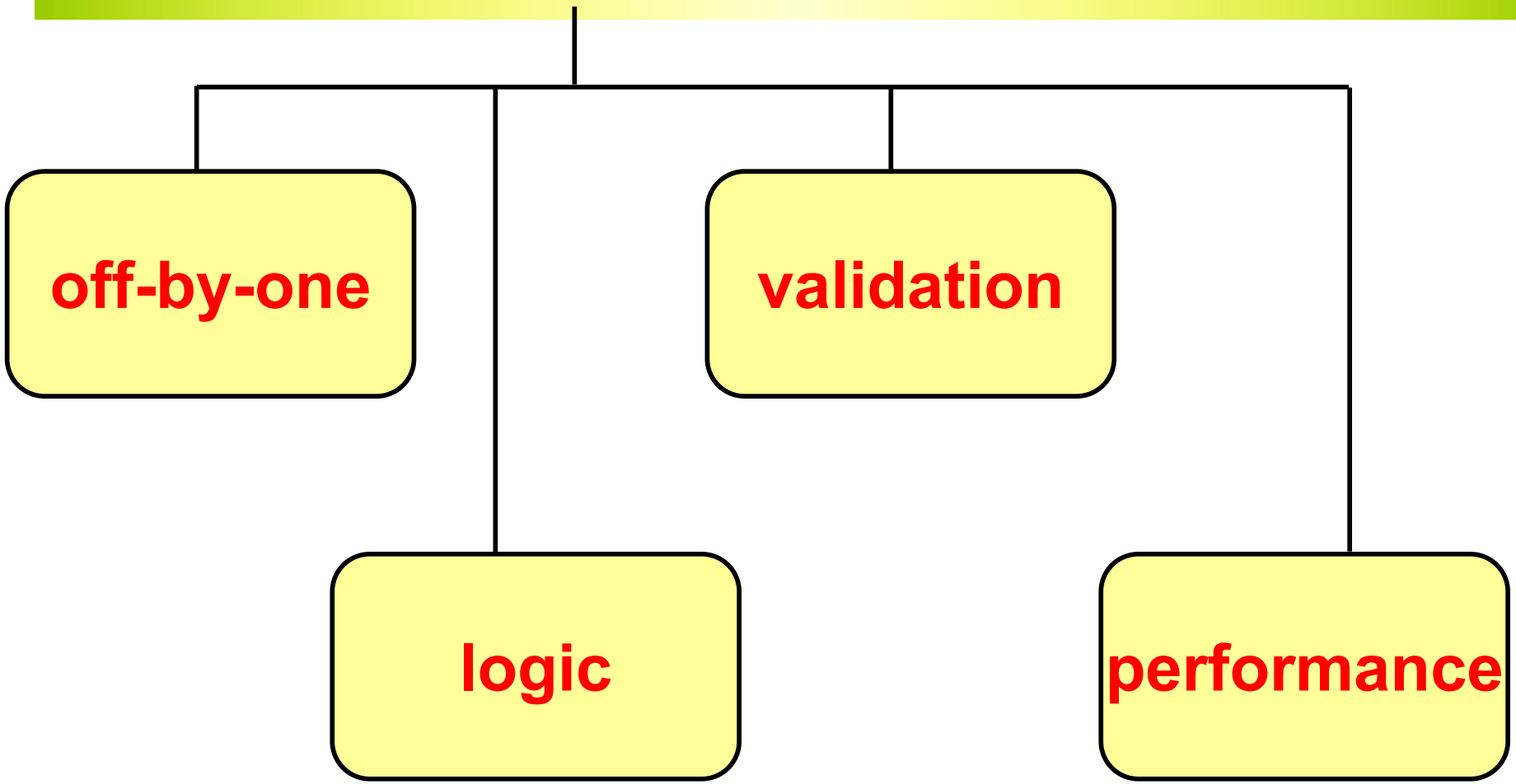


The Knuth/Barr Bug Categories

A – Algorithm	the code follows the intent of the programmer but the intent was wrong
D – Data	the code reads/writes incorrect data or accesses a wrong storage location
F – Forgotten	a missing action/statement or maybe it is in the wrong place in the program
B – Blunder	the algorithm was correct but it was implemented wrong or it was mistyped



A – Algorithm: Subcategories



A – Algorithm: Subcategories

off-by-one

Miscounting by one.

```
// count how many pages to print
pageCount = lastPage - firstPage;

// initialize the array
for( int i=0; i<=A.length; i++ ) {
      A[i] = 0;
}
```

A – Algorithm: Subcategories

logic

The algorithm is simply wrong

```
// find the greatest difference
// between any pair of elements
biggest = 0.0;
for( k = 0; k < A.length-1; k++ ) {
    distance = abs(A[k]-A[k+1]);
    if (distance>biggest)
        biggest = distance;
}
```

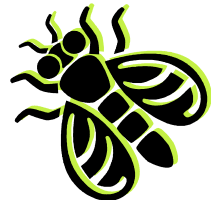
A – Algorithm: Subcategories

validation

Failure to check validity of variables

```
// find average difference
float avgDiff( float A[], int n ) {
    int i;  float sum = 0.0;
    for( i = 1; i<n; i++ )
        sum += abs(A[i]-A[i-1]);
    return sum/n;
}
```

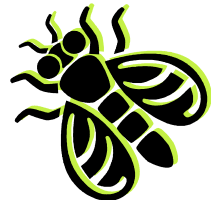
But what happens if n == 1 ?



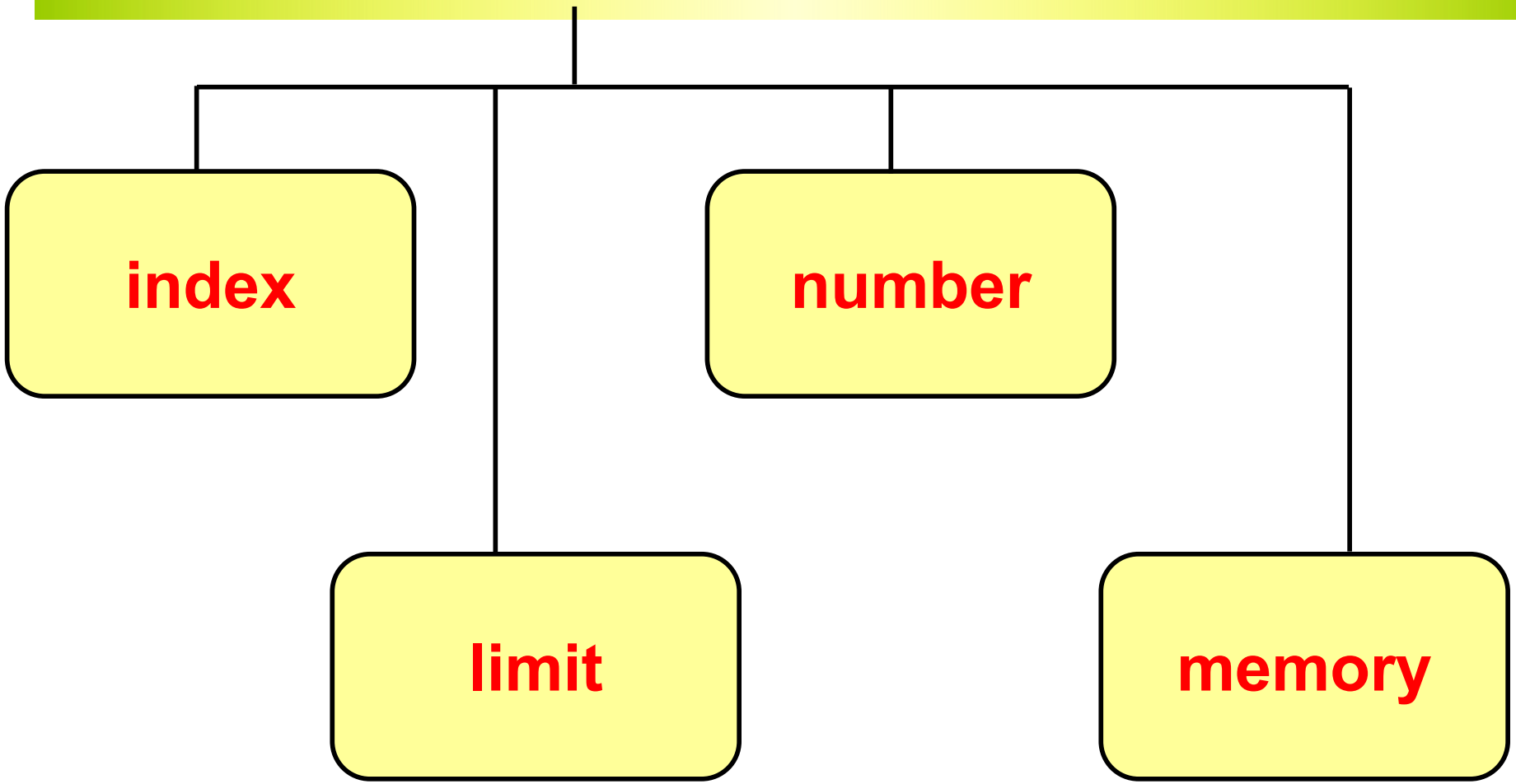
A – Algorithm: Subcategories

- an inappropriate algorithm, or
- a coding error which leads to unacceptable performance

performance



D – Data: Subcategories

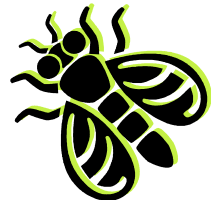


D – Data: Subcategories

index

An array index is wrong.

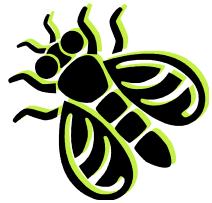
```
int search( int[] Array, int Val ) {
    int Hi = Array.length; int Lo = 0;
    while(Lo<=Hi) {
        int Mid = (Hi+Lo)/2;
        if (Array[Mid]==Val) return Mid;
        if (Array[Mid]<Val)
            Lo = Mid+1;
        else
            Hi = Mid-1;
    }
    return -1;
}
```



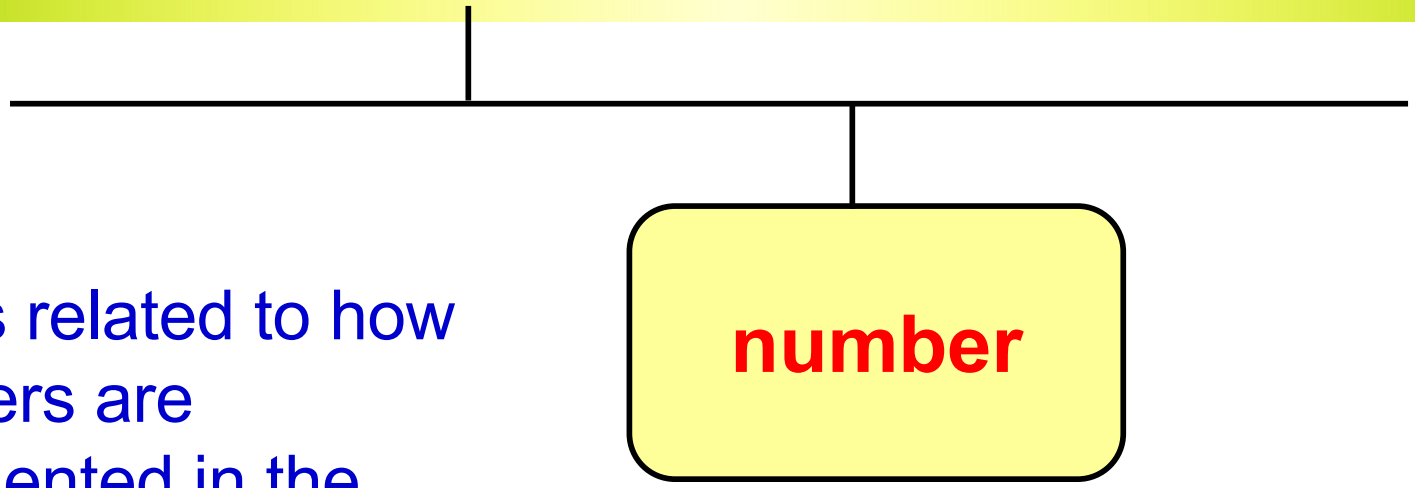
D – Data: Subcategories

Incorrect handling for the first or last elements in a sequence.

limit



D – Data: Subcategories



Issues related to how numbers are represented in the computer

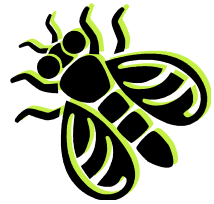
```
for( ; ; ) {
    unsigned char c = getchar();
    if (c == EOF) break;
    …
}
```

D – Data: Subcategories

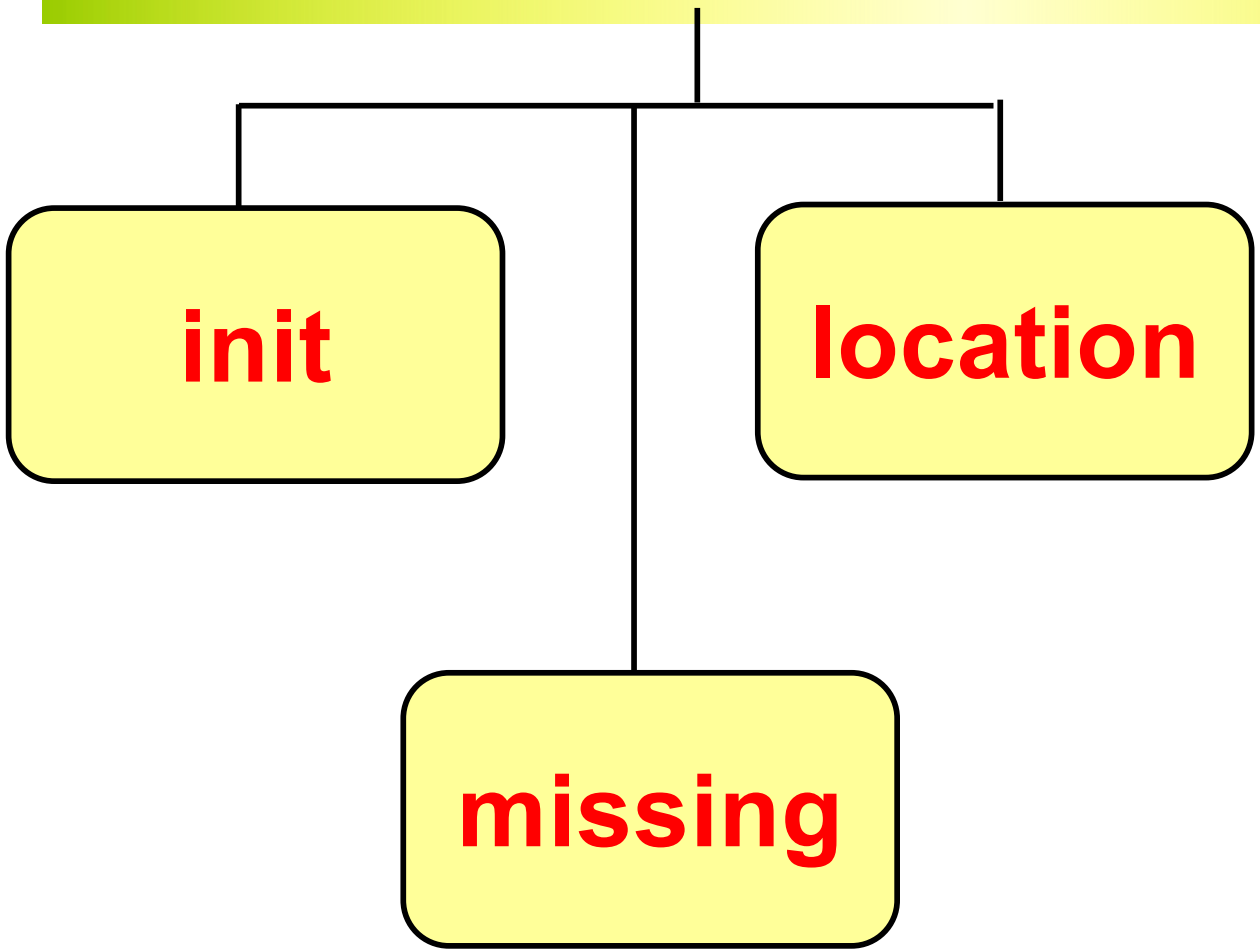
Mismanagement of memory – such as

- attempting to access an inaccessible location,
- or deallocating the same block twice, or
- failing to deallocate a block, or
- continuing to use a block after it has been deallocated.

memory



F – Forgotten: Subcategories



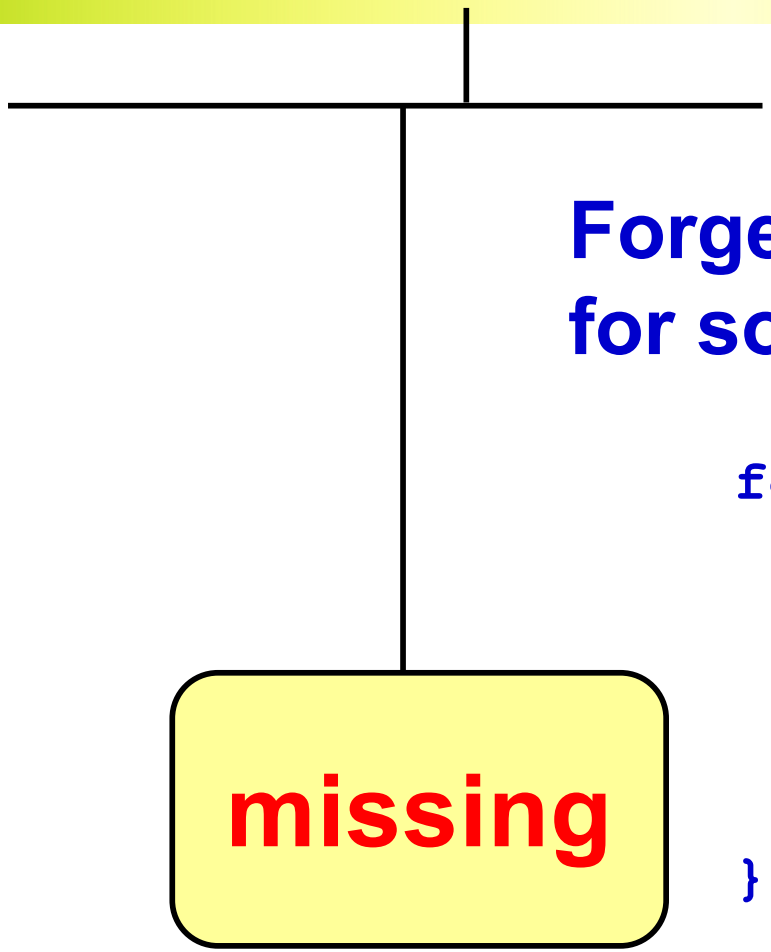
F – Forgotten: Subcategories

init

Forgetting to initialize a variable or a data structure

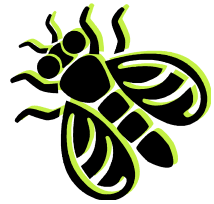
```
int biggest;
int i;
for( i=0; i<N; i++ ) {
    if (A[i] > biggest) biggest = A[i];
}
```

F – Forgotten: Subcategories

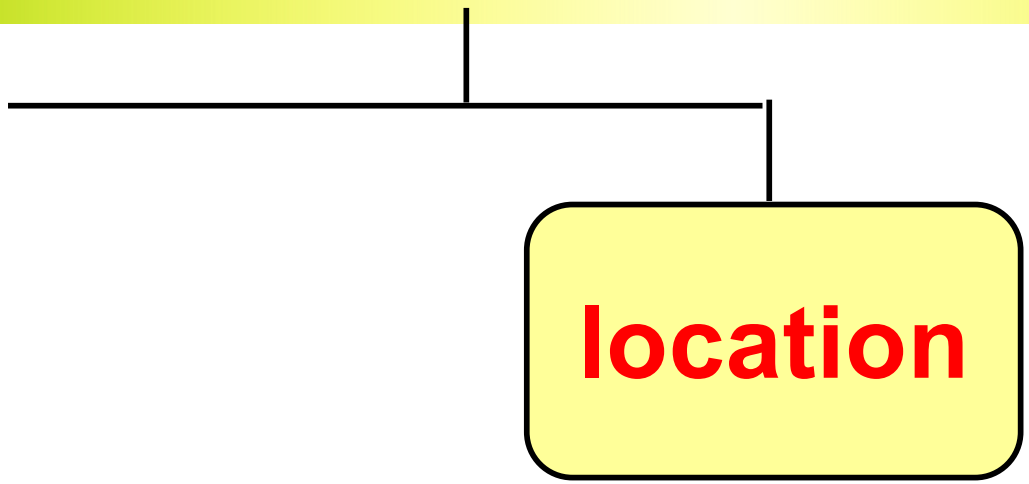


Forgetting to provide code for some case.

```
for( cnt=0; cnt<N; cnt++ ) {
    val = ptr->v;
    if (val < 0) continue;
    sum += val;
    ptr = ptr->next;
}
```

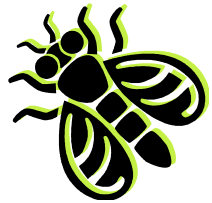


F – Forgotten: Subcategories

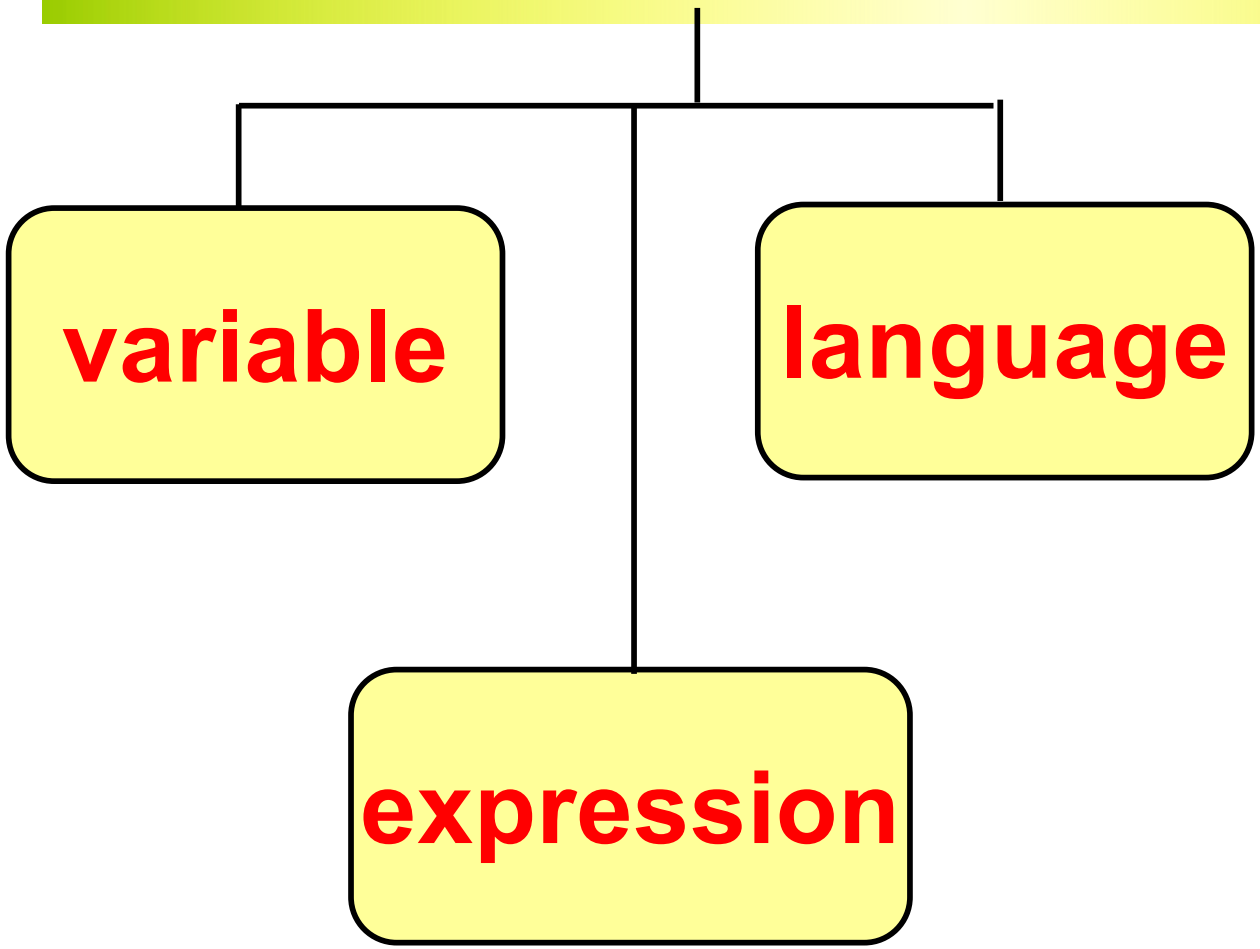


Code appears in the wrong place or is out of order.

```
array[ix] = 0;
sum += array[ix];
```



B – Blunder: Subcategories



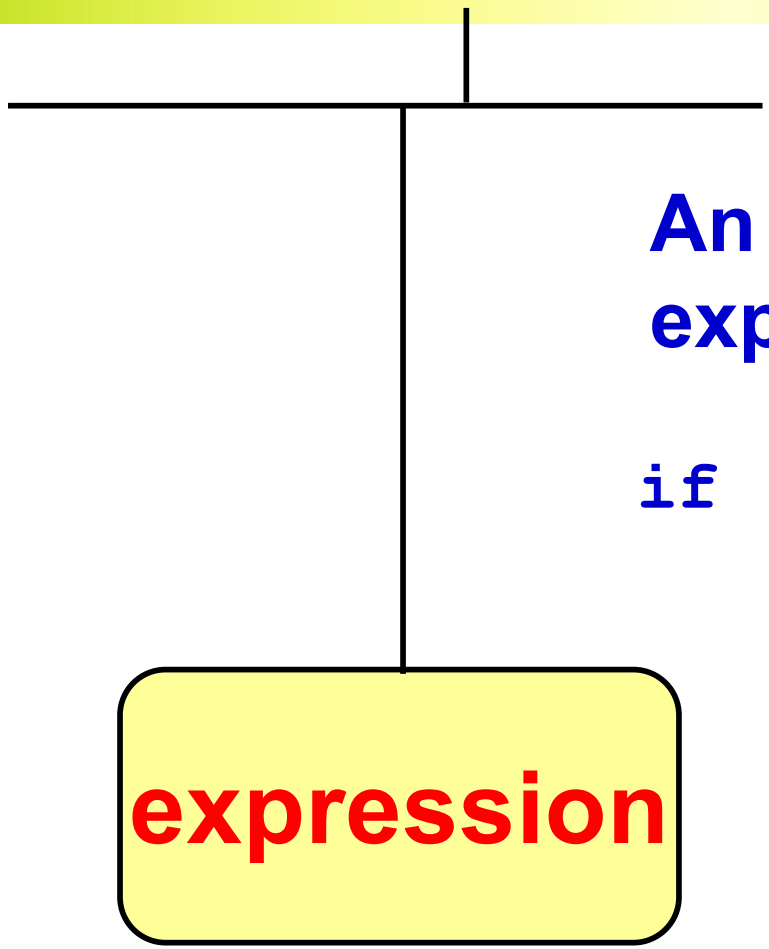
B – Blunder: Subcategories

variable

Simply writing the wrong variable name

```
x1 = transform(x1, x2, delta_x);
y1 = transform(y1, x2, delta_y);
```

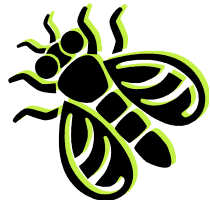
B – Blunder: Subcategories



An incorrectly written expression

```
if ((count < min) &&
      (count > max))…
```

||



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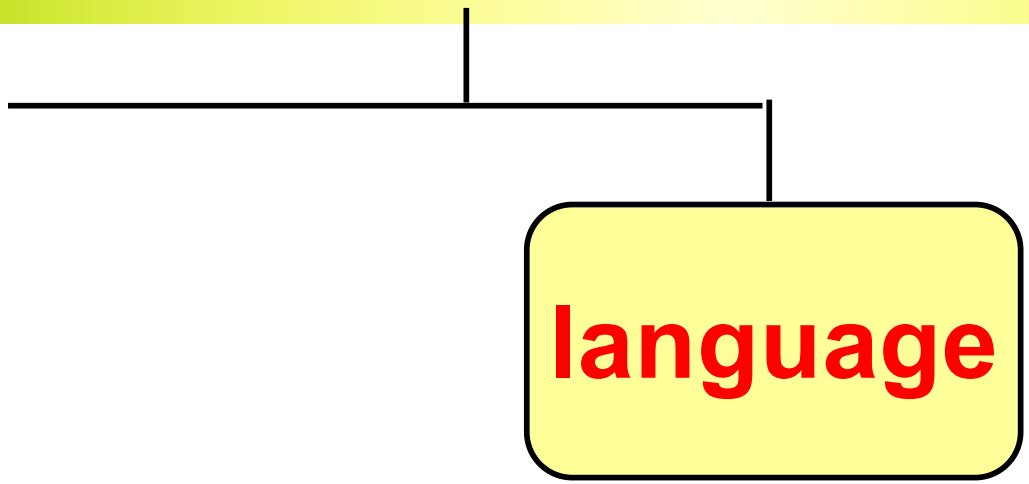
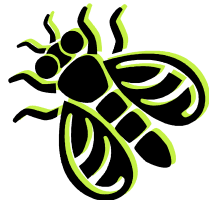


A mistake encouraged by the language syntax

==

```
if (a = b) { . . . }
```



Some Bug Avoidance Strategies

Use a High-Level Language

and obtain all the advantages of

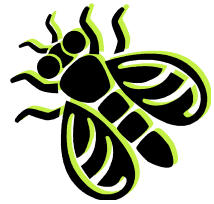
- strong type-checking at compile time,
- memory management,
- run-time checking of pointers, array indexes, arithmetic overflow, *etc*. (usually!).

Some Bug Avoidance Strategies

Think Before You Code

Depending on the size of the programming team and the size/scope of the project, you may want to:

- Write out and debug the specifications
- Plan the software architecture
- Design the data structures
- Develop pseudocode for the algorithms
- Prove the correctness of the algorithms



Some Bug Avoidance Strategies

Write Robust Code – the strategies include:

validate

assertions

reuse

check results

KISS

watch out for gotchas

Some Bug Avoidance Strategies

Write Robust Code – the strategies include:

- validate
- assertions
- reuse
- check results
- KISS
- watch out for gotchas

Every subroutine should validate its inputs (unless there is a clear *proof* that the inputs will always be valid)

Some Bug Avoidance Strategies

Write Robust Code – the strategies include:

- validate
- assertions
- reuse
- check results
- KISS
- watch out for gotchas

Insert assertions to verify that pointers are non-null and array indexes are in range (unless guaranteed by the programming language)

Some Bug Avoidance Strategies

Write Robust Code – the strategies include:

validate

assertions

reuse

check results

KISS

watch out for gotchas

Use library functions and library classes wherever possible (they have already been debugged!)

Some Bug Avoidance Strategies

Write Robust Code – the strategies include:

validate

assertions

reuse

check results

KISS

watch out for gotchas

Library functions often return codes to indicate exceptional conditions – be sure to check them!

Some Bug Avoidance Strategies

Write Robust Code – the strategies include:

- validate
- assertions
- reuse
- check results
- KISS
- watch out for gotchas

"Keep It Simple, Stupid!"

Avoid complicated logic in your programs; it will probably cost you more debugging time than it saves in execution time

Some Bug Avoidance Strategies

Write Robust Code – the strategies include:

- validate
- assertions
- reuse
- check results
- KISS
- watch out for gotchas

Many programming languages have common pitfalls, such as

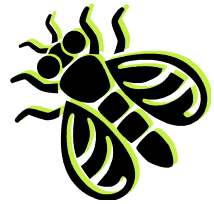
```
if (a = true) { … }
```

in C, C++, Java, C#.

Some Bug Avoidance Strategies

Test Your Code!

- Testing actually *finds* bugs rather than avoids bugs, but a failure which is found early (before releasing the program) and on a simple test case is much easier to analyze.
- Including test methods in classes (or test functions in modules) is a good idea.



Bug Detection – Step 1

- Study the failure symptoms to identify (if possible)
  - where in the program the fault occurred and
  - what the program state must have been.
- If necessary add an exception handler to the program (or use a debugging tool), to determine exactly where the error occurs.

Bug Detection – Step 2

- Read and re-read your code in the vicinity of the error location.
  - Better still, have *someone else* read your code.
  - Alternatively find a person who will listen and explain the program's logic to him or her.

Bug Detection – Step 3

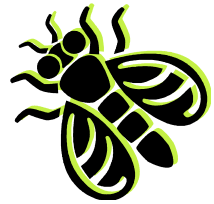
- Experiment to find the simplest / shortest input which causes the failure to occur.
- Disable compiler optimization (if enabled).
- And try to develop theories about the program state which, if reached, would case the observed failure.

These preliminaries will make life much easier for the following steps.

Bug Detection – Step 4

We can try inserting …

- assertions at strategic points to verify that an erroneous program state is not being entered, and/or
- output statements at strategic points to determine whether variables are taking on erroneous values.



Bug Detection

Perhaps the preceding steps have helped track down the error?

But maybe not …

- There is too much trace output to examine?
- We didn't capture the right information?
- The bug went away when we inserted those extra statements????

The “Heisenbug”

- It is a bug which changes or goes away when you try to observe it.
- How can this happen?
- The addition of code changes the addresses of variables and subroutines, and may affect the positions of objects on the heap and times when a garbage collection occurs. An array indexing error or an invalid pointer may access a different data item and lead to different behaviour …

Heisenberg in 1927

The Debugger

Sometimes we need to observe our bug in an unchanged copy of the program.

We need to have one program watch another program.

The watcher is called a *debugger* (and the program being monitored is the *debuggee*).

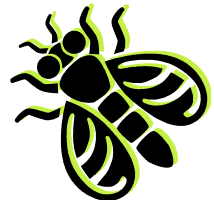
The Debugger

Two Common Tasks

analysis of crash dumps

monitoring an executing program to watch it go wrong

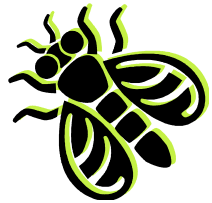
Often, a single tool will perform either task



The Debugger – Note!

There is **no** guarantee that the debuggee will behave in exactly the same way with a debugger

Perhaps it's a timing dependency?
Or perhaps the debuggee's memory layout is different?



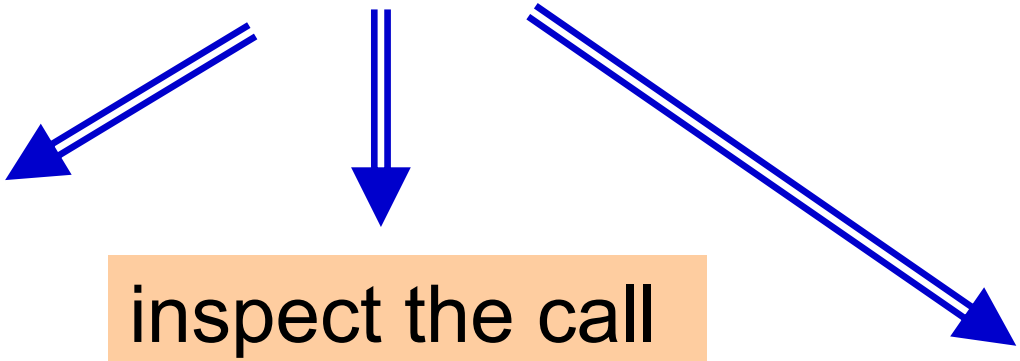
Some Debuggers

- Visual Studio on Windows
- dbx and gdb for debugging C/C++ … on Unix
- eclipse for debugging Java (and other languages)
- jdb for debugging Java
- IDLE for debugging Python

- *insight* is a GUI front-end for for gdb
- *DDD* (Data Display Debugger) is a GUI front-end for gdb/dbx/jdb/…

Analysis of Crash Dumps

The debugging tool provides the ability to



discover where the program crashed and why

inspect the call stack and the parameters

inspect the values of variables

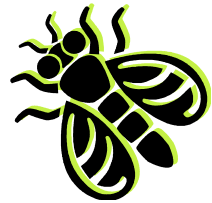
Note: the first two features are provided by a stack trace when an exception is caught in Java or C#.

From Static to Dynamic ...

Static Tools	Dynamic Tools
Source code analysis (to check compliance to coding standards, warn about possible problems)	Resource usage monitoring (CPU and memory profilers) e.g. jstat, jconsole, jprofiler, Prof-It, …
Crash dump inspection	**Debuggers**

Common Monitoring Facilities Provided by Debuggers

- Breakpoints
- Single step execution
- Inspect variables, location
- Display source code
- Fault detection
- Watchpoints
- Multithread, multiprocess support



Common Monitoring Facilities Provided by Debuggers

- Breakpoints
- Single step execution
- Inspect variables, location
- Display source code
- Fault detection
- Watchpoints
- Multithread, multiprocess support

```
(gdb) break main
(gdb) break 22
```

Run program until a breakpoint is reached

↓

Inspect values of variables

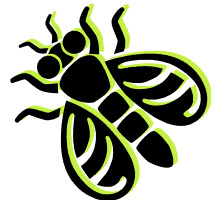
↓

Resume execution

Common Monitoring Facilities Provided by Debuggers

- Breakpoints
- Single step execution
- Inspect variables, location
- Display source code
- Fault detection
- Watchpoints
- Multithread, multiprocess support

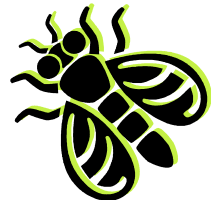
`step`	execute one statement and stop again
`next`	execute one statement or a complete method/function call and stop again



Common Monitoring Facilities Provided by Debuggers

- Breakpoints
- Single step execution
- Inspect variables, location
- Display source code
- Fault detection
- Watchpoints
- Multithread, multiprocess support

```
(gdb) print sum
(gdb) where
(gdb) up
```



Common Monitoring Facilities Provided by Debuggers

- Breakpoints
- Single step execution
- Inspect variables, location
- Display source code
- Fault detection
- Watchpoints
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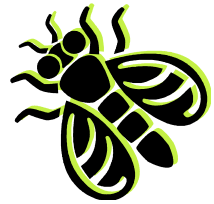
```
(gdb) list main
(gdb) list encode
(gdb) list 22
```



Common Monitoring Facilities Provided by Debuggers

- Breakpoints
- Single step execution
- Inspect variables, location
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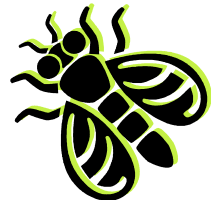
If the debuggee thows an exception or performs some illegal action, the debugger must re-take control and give the user a chance to inspect the situation



Common Monitoring Facilities Provided by Debuggers

- Breakpoints
- Single step execution
- Inspect variables, location
- Display source code
- Fault detection
- Watchpoints
- Multithread, multiprocess support

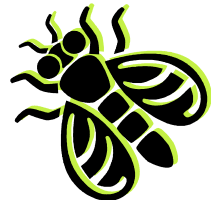
```
watch sum
```

watches for accesses to a variable, breaks when value in variable is changed

Common Monitoring Facilities Provided by Debuggers

- Breakpoints
- Single step execution
- Inspect variables, location
- Display source code
- Fault detection
- Watchpoints
- Multithread, multiprocess support

Ability to monitor execution of individual threads or processes in the debuggee



Styles of Debuggers

Command-Line

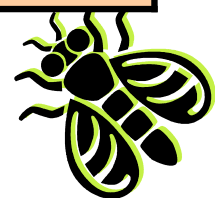
- gdb and jdb are examples

Graphical User Interface

- Visual Studio, eclipse, IDLE, gdb+DDD are examples

Epic Failures: 11 Software Bugs (ComputerWorld, 9 Sept. 2010)

1998	Mars Climate Orbiter didn't orbit
1962	Mariner 1 went off course
1996	Ariane 5 Flight 501
1994	Faulty Floating-Point Math in Intel Pentium
1990	AT&T Network Outage
2007	Windows 'Genuine Advantage' was buggy
1991	Patriot Missiles mistimed
1985-1987	Therac-25 Medical Accelerator
2001	Cobalt-60 Overdoses
2000	Osprey Airplane/Helicopter Crash
1983	Soviet Missile Defense Early-Warning System



Some Further Reading on Debuggers/Debugging

- Adam Barr. ***Find The Bug***. Addison Wesley, 2005. **`http://www.findthebug.com/`**
- E. Allen. ***Bug Patterns in Java***. Apress, 2002.
- S.L. Bartlett, A.R. Ford, T.J. Teorey, G.S. Tyson. ***Practical Debugging in Java***. Pearson, 2004.
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