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Sanitizing Sensitive Data: How to get it Right (or at least Less Wrong…)

Roderick Chapman, 14th June 2017

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The problem…

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- "Secure coding" standards call for "sanitization" of "sensitive" data after it has been used.
  - What does this actually mean?
  - How do you do it?
  - How do you know you've got it right?
  - Oh.. and we had to do this for a client project, to meet GCHQ evaluation standards…

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The problem…

- Standards survey:
  - GCHQ IA Developers' Note 6: Coding Requirements and Guidance
  - CERT Coding Standards
  - ISO SC22/WG23 Technical Report 24772
  - Common Weakness Enumeration (CWE)
  - Cryptography Coding Standard

The problem…

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- GCHQ IA Developers' Note 6: Coding Requirements and Guidance

  "Sanitise all variables that contain sensitive data (such as cryptovariables and unencrypted data) … sanitisation may require multiple overwrites or verification, or both."

  "if a variable can be shown to be overwritten shortly afterwards, it may be acceptable not to sanitise it, provided it is sanitised when it is no longer needed. 'Shortly' is not defined more precisely, since it will depend on the situation"

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The problem…

- GCHQ IA Developers' Note 6: Coding Requirements and Guidance

  "Sanitise all variables that contain sensitive data (such as cryptovariables and unencrypted data) … sanitisation may require multiple overwrites or verification, or both."

  "if a variable can be shown to be overwritten shortly afterwards, it may be acceptable not to sanitise it, provided it is sanitised when i
  'Shortly' is not defined more p
  on the situation"

What does this actually mean?

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Technical issues

- So why not just “write zeroes” to the variable?

```
declare
    T : Word32;
begin
    -- Do stuff with T;

    -- Now sanitize T
    T := 0;
end;
```

Technical issues

- So why not just “write zeroes” to the variable?
  - T is local, therefore final assignment is *dead* in information-flow terms.
  - Optimizing compilers can remove the final assignment. Oops!
    - Modern compilers try *very hard* to remove redundant loads and stores.
  - “All zeroes” might not be a valid value, so can a legal assignment statement be written at all?

Technical issues

- Derived values and copies…
- If A and B are “sensitive”, then

```
C := A op B;
```

- Is C also “sensitive”? Does C require sanitization?
- What about copies of sensitive date – in compiler-generated local variables, CPU registers, data cache? How do you sanitize those (without assembly language programming…)?

Technical issues

- By-Copy parameter passing…
- See above – copies are bad!
- How do you sanitize a By-Copy “in” parameter anyway???

Technical issues

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- CPU data caching and memory hierarchy.
- Memory subsystem in a modern CPU is really really complicated!
  - Multiple levels of cache.
  - Instruction re-ordering and write coalescing etc. etc.
  - Register renaming (more copies!)
  - Operating system paging and virtual memory? Has a copy of my sensitive data been written to disk?!?!

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Design goals…

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- For a recent project…design constraints and goals:
  - Sanitization code in source Ada and/or SPARK – no assembly language required.
  - Portable – no use of non-portable or implementation-defined language features.
  - “Bare metal” embedded target, so compatibility with GNAT Pro Zero-FootPrint (ZFP) runtime library.
  - Compatible with both SPARK 2005 and SPARK 2014 languages and verification tools.
  - “Just works” (with confidence) at *any* compiler optimization level.

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- The problem…
- Technical issues
- Design goals
- **Ada language support**
- A policy for sanitization
- Related and further work

Ada support

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- Various language mechanisms were investigated, including…
  - Controlled Types
  - Volatile aspect
  - Limited and By-Reference types
  - Inspection_Point pragma
  - No_Inline aspect

Controlled Types

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- Define a “Finalize” procedure that does the sanitization?
- Tempting, but…
  - Significant support from the runtime library required, so no chance of this working with ZFP.
  - Not allowed by SPARK anyway.
  - Complex (i.e. not very well understood) semantics and implementation issues.
- Therefore…rejected!

Volatile

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- Easy! Just mark a sensitive object as Volatile, and the compiler will respect the reads and writes exactly as indicated in the source code…
- Better still … use Volatile *Types* for all sensitive data.
- Looks good, but…

Volatile

- Problems with Volatile

1. It is a blunt instrument – it preserves *all* reads and writes of an object, not just the “last one”, so some performance penalty…
2. Compilers don’t always get it right anyway…

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Volatiles Are Miscompiled, and What to Do about It

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ABSTRACT

C's volatile qualifier is intended to provide a reliable link between operations at the source-code level and operations at the memory-system level. We tested thirteen production-quality C compilers and, for each, found situations in which the compiler generated incorrect code for accessing volatile variables. This result is disturbing because it implies that embedded software and operating systems—both typically coded in C, both being bases for many

as volatile, the C compiler must ensure that every use (read or write) of that location in the source program is realized by an appropriate memory operation (load or store) in the compiled program. Accesses to volatiles are considered to be side-effecting operations, and they are therefore part of the observable behavior of a program that must not be changed by an optimizing compiler. Embedded software commonly relies on volatile variables in order to access memory-mapped I/O ports, to communicate between concurrent

- Paper from EMSOFT 2008.
- Have compilers improved? Not sure…
- Are "commercial" compilers better than "open source" (e.g. GNAT Pro vs FSF GCC vs LLVM)? Don't know…

Limited types

- A very useful mechanism in Ada…
  - No assignment by default. Good!
  - Passed By-Reference, so no copies. Good!

By-Reference types

- Another useful mechanism in Ada, and useful where limited types are not appropriate.

- Some types are defined to be “By Reference”, so avoids copying of sensitive parameters, for example
  - Tagged types (RM 6.2(5))
  - Record with Volatile component (RM C.6(18))

- GNAT –gnatRm flag can be used to verify passing mechanism chosen for each parameters of each subprogram.

Inspection_Point

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- Added to Annex H in Ada 95, but little used (or understood?)

- *Very* useful requirement in RM H 3.2(9):

  ‘The implementation is not allowed to perform “dead store elimination” on the last assignment to a variable prior to a point where the variable is inspectable. Thus an inspection point has the effect of an implicit read of each of its inspectable objects.’

- Exactly what we want! But…

Inspection_Point

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- How does it work?

- GNAT sources ada/gcc-interface/trans.c, in function Pragma_to_gnu ()

```
tree gnu_expr = gnat_to_gnu (gnat_expr);
...
ASM_VOLATILE_P (gnu_expr) = 1;
```

- So … see concerns above over correct compilation of Volatile.

No_Inline

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- Regehr recommends using a subprogram to perform the santization, and making sure that subprogram *can never be inlined*.
- This is intended to prevent inlining and subsequent optimization of the sanitizing assignment.

Pattern 1

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- Combining these ideas yields a pattern for a sanitized abstract data type:

```
package Sensitive is
   type T is limited private; -- so no assignment

   procedure Sanitize (X : out T);
   pragma No_Inline (Sanitize);
private
   type T is limited record -- so by-reference
      F : … -- and so on…
   end record;
end Sensitive;
```

Pattern 1

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- To allow for alternative implementations (i.e. for different targets/operating systems), the body of Sanitize is supplied as a separate subunit.
- For a ZFP/Bare-Metal target, we might write:

```
separate (Sensitive)
procedure Sanitize (X : out T) is
begin
      X.F := 0; -- or other valid value
      pragma Inspection_Point (X);
end Sanitize;
```

SPARK

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- In both SPARK 2005 and SPARK 2014, a sanitizing assignment is reported as “Ineffective” by information-flow analysis.
- So ... expect this, and justify:

```
pragma Warnings (Off, “unused assignment”,
                 Reason => “Sanitization”);
T := 0;
pragma Inspection_Point (T);
```

SPARK

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- What about proof?
- For non-limited types, we could declare a constant for the “sanitized value”, and use that in post-conditions and/or assertions.
  - Note, though, that the value of the constant must be valid, so a value with representation 2#0000_0000_…# might not be OK.
- For limited types, we could declare a Boolean-valued function, thus:

SPARK

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```
package Sensitive is
   type T is limited private; -- so no assignment

   function Is_Sanitized (X : in T) return Boolean;

   procedure Sanitize (X : out T)
      with Post => Is_Sanitized (X);
   pragma No_Inline (Sanitize);

private
   -- As before…
end Sensitive;
```

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Policy

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- Identification and Naming
  - Project must clearly define what is “sensitive”.
  - Consider global and local variables carefully…
  - May also depend on physical characteristics of memory (e.g. Stack might be in “secure RAM”, but library-level data isn’t…)

Policy

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- Identification and Naming
  - Sensitive *constants* are not permitted.
  - Define a naming convention for sensitive types, variables and formal parameters.
  - Choose convention to facilitate automated search of compiler and tool output.

Policy

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- Types and Patterns
  - Use by-reference types for sensitive data.
  - Use limited types as per Pattern 1 above where possible.
  - Use pragma Warnings to suppress SPARK flow error.

Policy

- Compiler switches
  - Use –gnatwa to get “useless assignment” warning enabled.
  - Use –gnatRm to verify passing mechanism.
  - Use –g and –fverbose-asm to check generated code if necessary.

Contents

Related and Further Work (1)

- Special compiler switch to automatically sanitize local data?
  - -ferase-stack perhaps?
  - Actually, this has already been done by the team at www.embecosm.com in GCC and LLVM.
  - Will it work with Ada?

Related and Further Work (2)

- What about a new language-defined Aspect?

```
Key : Word32 with Sensitive; -- ???
```

- Then compiler takes care of it?

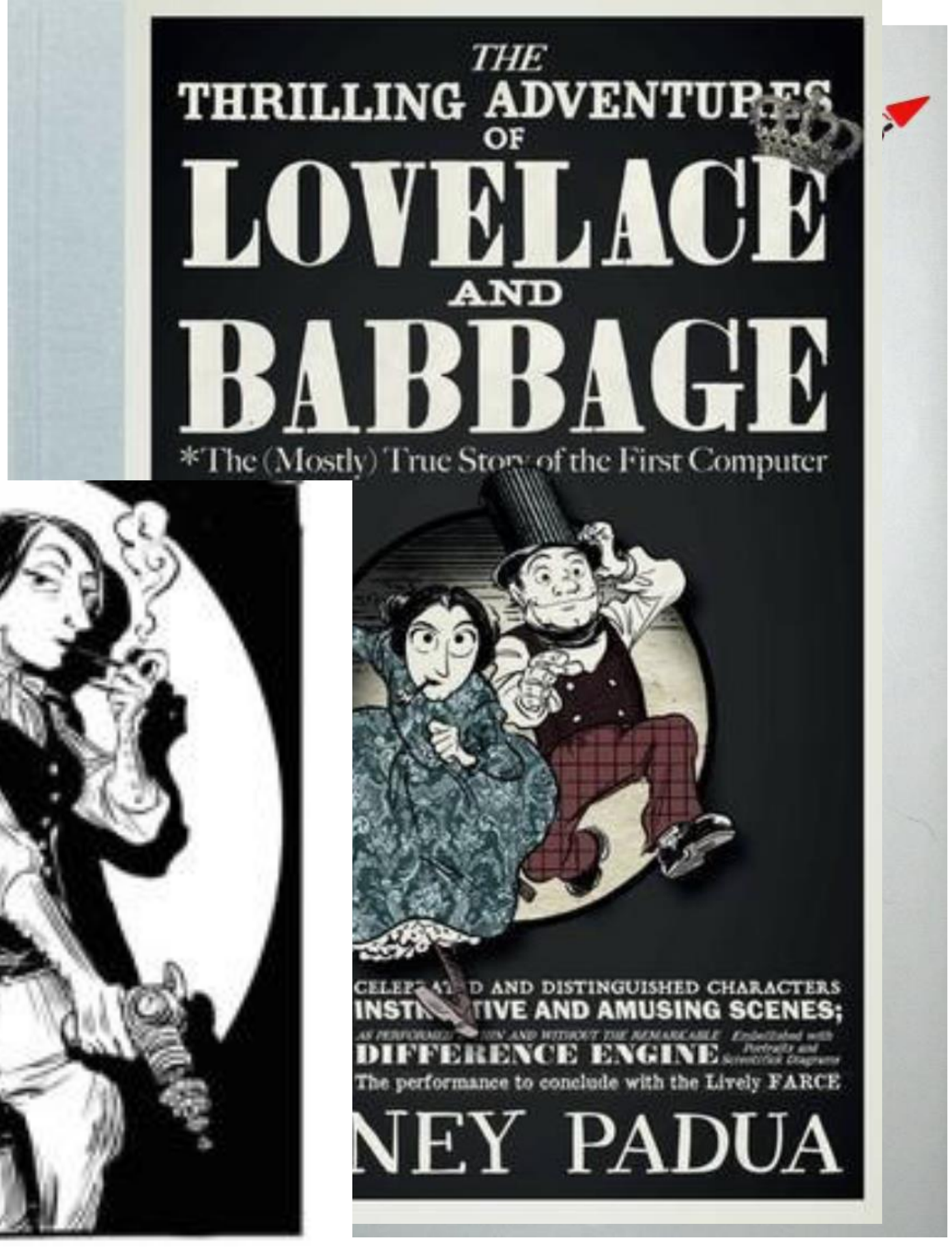
Related and Further Work (3)

- A binding to C11 “stdatomic” library would be good…
- Provides portable access to “memory fence” instructions and so on…

Related and Further Work (4)

- What is the impact of Link-Time Optimization (LTO)?
  - No idea…
- Can we use information-flow analysis to track values derived from sensitive data?
  - Like “taint analysis” in other languages…

Homework…


THE
THRILLING ADVENTURES
OF
LOVELACE
AND
BABBAGE
*The (Mostly) True Story of the First Computer
D AND DISTINGUISHED CHARACTERS
TIVE AND AMUSING SCENES;
DIFFERENCE ENGINE
The performance to conclude with the Lively FARCE
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Questions…

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