1. Programming Languages for Writing Safety-Critical Software

Remark:

This section is based heavily on Neil Storey [St96], *Safety-critical computer systems*, Addison-Wesley, 1996, pp. 218 - 227.
Criteria for Choice of Languages

Main Criteria for Choice of Programming Languages for Critical Systems

- **Logical soundness.**
  - Is there a sound, unambiguous definition of the language?

- **Complexity of definition.**
  - Are there simple, formal definitions of the language features?
  - Too high complexity results in high complexity and therefore in errors in compilers and support tools.
Criteria for Choice of Languages

Expressive power.

Can program features be expressed easily and efficiently?

The easier the program one has written, the easier it is to verify it.
Criteria for Choice of Languages

Security.

Can violations of the language definitions be detected before execution?

Some interpreted languages detect errors only when running it.

Various languages like Eiffel and (early?) versions of generic Java allow to define programs, which
  · the compiler regards as type correct,
  · although they aren’t,
  · run time errors are caused by this.
Criteria for Choice of Languages

- **Verifiability.**
  - Is there support for verifying that program code meets the specification?

- **Bounded space and time requirements.**
  - Can it be shown that time and memory constraints are not exceeded?
Reasons for Program Errors

Common Reasons for Program Errors:

- **Subprogram side-effects.**
  - Variables in the calling environment are unexpectedly changed.

- **Failure to initialise.**
  - Variable is used before it is initialised.
Reasons for Program Errors

- **Aliasing.**
  - Two or more distinct names refer to the same storage location.
  - Changing one variable changes a seemingly different one.
Example Aliasing Problem

The following is a way of exchanging two Boolean values without the use of a temporary variable:

\[
\begin{align*}
x &= x \text{ xor } y; \\
y &= x \text{ xor } y; \\
x &= x \text{ xor } y;
\end{align*}
\]
Exchange Procedure

The exchange program exchanges the arguments because if we give different names to the instances of variables

\[ x_1 = x \text{xor} y; \]
\[ y_1 = x_1 \text{xor} y; \]
\[ x_2 = x_1 \text{xor} y_1; \]

we get (using associativity, commutativity of xor and \(x \text{xor} x = \text{false}, x \text{xor} \text{false} = x\))

\[ y_1 = x_1 \text{xor} y = (x \text{xor} y) \text{xor} y = x \text{xor} (y \text{xor} y) \]
\[ = x \text{xor} \text{false} = x \]
\[ x_2 = x_1 \text{xor} y_1 = (x \text{xor} y) \text{xor} x = y \text{xor} (x \text{xor} x) \]
\[ = y \text{xor} \text{false} = y \]
Exchange Procedure

Doing the above bitwise we can exchange as well integers.
In order to write a procedure for exchanging Booleans we need to use a small wrapper class:

```java
class MyBool {
    public boolean theBool;
    MyBool (boolean x) { theBool = x; }
}
```

Now write the exchange function as follows (\( \hat{\lor} = \text{xor} \))

```java
void exchange(MyBool x, MyBool y) {
    x.theBool = x.theBool \( \hat{\lor} \) y.theBool;
    y.theBool = x.theBool \( \hat{\lor} \) y.theBool;
    x.theBool = x.theBool \( \hat{\lor} \) y.theBool;
}
```
Example Aliasing Problem

```c
void exchange(MyBool x, MyBool y) {
    x.theBool = x.theBool ^ y.theBool;
    y.theBool = x.theBool ^ y.theBool;
    x.theBool = x.theBool ^ y.theBool;
};
```

- If x and y are the same object the above sets x.theBool to false:
  The last line then reads
  ```c
  x.theBool = x.theBool ^ x.theBool;
  ```
  which sets (using \( x \ xor \ x = \text{false} \)) \( x \) \( \times \)theBool = false

- So if \( x \times \)theBool was true, and x and y happen to be the same object, the above method is not an exchange function.
void exchange(MyBool x, MyBool y) {
    if (x != y) {
        x.theBool = x.theBool ^ y.theBool;
        y.theBool = x.theBool ^ y.theBool;
        x.theBool = x.theBool ^ y.theBool;
    }
};

Reasons for Program Errors

- **Expression evaluation errors.**
  - E.g. out-of-range array subscript, division by zero, arithmetic overflow.
  - Different behaviour of compilers of the same language in case of arithmetic errors.
Comparison of Languages

Cullyer, Goodenough, Wichman have compared suitability of programming languages for high integrity software by using the following criteria:

- **Wild jumps.**
  - Can it be guaranteed that a program cannot jump to an arbitrary memory location?
  - By use of gotos.

- **Overwrites.**
  - Can a language overwrite an arbitrary memory location?
  - C, C++ can do so.
Comparison of Languages

Semantics.

Is semantics defined sufficiently so that the correctness of the code can be analysed?
Comparison of Languages

Model of mathematics.

Is there a rigorous definition of integer and floating point arithmetic (overflow, errors)?
- E.g. in Java, floating point arithmetic is defined as following the IEEE floating point arithmetic.
  - States precisely when we get an overflow etc. and what to do if we have an overflow.

If this is not precisely defined, a program might
- run perfectly on the machine used for testing it (which ignores an error)
- and might crash on the machine, it is actually running.
Operational arithmetic.

Are there procedures for checking that the operational program obeys the model of arithmetic when running on the target processor?

E.g. programs which determine, whether the processor follows the IEEE floating point standard.
Comparison of Languages

- **Data typing.**
  - Are there means of data typing that prevent misuse of variables?

- **Exception handling.**
  - Is there an exception handling mechanism in order to facilitate recovery if malfunction occurs?
Comparison of Languages

- Exhaustion of memory.
  - Are there facilities to guard against running out of memory?
  - **Object-oriented** and **functional** programming languages have a problem here, since memory is allocated on the fly.
  - Potential problem of **garbage collection**, if it is executed in a time-critical situation (e.g., the autopilot might carry out garbage collection, while landing).
  - **Recursion** is as well problematic, since the depth of recursion cannot be controlled, and each recursion step requires usually the allocation of new memory.
Comparison of Languages

Safe subsets.

Is there a safe subset of the language that satisfies requirements more adequately than the full language?
Comparison of Languages

Separate compilation.

Is it possible to compile modules separately, with type checking against module boundaries?

It should be possible to split the program into units (packages, classes), which are located in different files, with separate interface definitions.

This allows to verify the correctness of each unit individually, and avoids the danger that exchanging one unit destroys the correctness of already verified units.
Comparison of Languages

- Well-understood.
  - Will designers and programmers understand the language sufficiently to write safety critical software?
Comparison of Languages

Legend for next slide:

+ means protection available,
? means partial protection,
- means no protection.
## Comparison of Languages

<table>
<thead>
<tr>
<th></th>
<th>Structured assembler</th>
<th>C</th>
<th>CORAL 66</th>
<th>ISO PASCAL</th>
<th>Modula 2</th>
<th>Ada</th>
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</thead>
<tbody>
<tr>
<td>Wild jumps</td>
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<td>Overwrites</td>
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<td>Safe subsets</td>
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<td>Separate compil.</td>
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<tr>
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Remarks on CORAL 66

- CORAL 66 = compiled structured programming language related to Algol.
- Developed at the Royal Radar Establishment RRE, Malvern, UK.
- Used for real-time systems.
- Allowed inline assembly code.
- No free CORAL 66 compilers seem to be available today.
Analysis

- C most unsuitable language.
- Modula-2 most suitable.
  - Problem of Modula-2: **limited industrial use**.
  - Therefore lack of tools, compilers.
  - Industrial use contributes to reliability of compilers.
    - Case study revealed:
      Compiler faults are equivalent to one undetected fault in 50 000 lines of code.
      - Especially problem of optimisation.
      - By using compilers heavily compilers are tested and compiler errors are detected and removed.
Analysis (Cont.)

- One solution: development of new languages for high integrity software.
  - Same problem as for Modula-2: limited industrial use.

- Better solution: introduction of safe subsets.
  - Rely on standard compilers and support tools.
  - Only additional checker, which verifies that the program is in the subset.
  - Add annotations to the language.
# Safe Subsets

<table>
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<tr>
<th>Feature</th>
<th>CORAL subset</th>
<th>SPADE-Pascal subset</th>
<th>Modula2 subset</th>
<th>Ada subset</th>
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Programming Languages Used

- **Aerospace.**
  - Trend towards Ada.
  - Use of languages like FORTRAN, Jovial, C, C++.
  - 140 languages used in the development of the Boeing 757/767.
  - 75 languages used in development of the Boeing 747-400.
  - E.g. C++ for the seat back entertainment system of Boeing 777.
  - Northrup B2 bomber control system: C++
Aerospace (Related).

- Air traffic control systems in US, Canada, France: Ada.
- Denver Airport baggage system written in C++, but initial problems probably not directly related to the use of C++.
- Problems with the software for the Denver Airport baggage system delayed the opening of this airport by one year.
- The economic damage caused by these problems shows that this software has some aspects of a business critical system.
- But that’s a degree of critically which applies to almost all business software.
Programming Languages Used

Spacecraft.

- European Space Agency: use of Ada in mission-critical systems.
- Space shuttle: Hal/s and Ada plus other languages.
Programming Languages Used

- **Automotive systems:**
  - Much assembler. Also C, C++, Modula-2

- **Railway industry:**
  - Ada as de-facto standard.

- **In general:**
  - Trend towards Ada for the high-integrity parts of the software.
  - Use of assembler, where necessary.