FROM RESEARCH TO INDUSTRY

cea tech

FORMAL VERIFICATION OF EMBEDDED SOFTWARE

THROUGH FRAMA-C

list

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CEA LIST

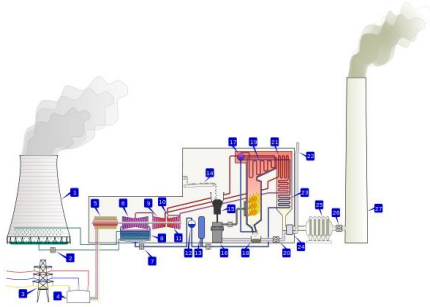
OUTLINE

- **Formal verification of embedded software through Frama-C**
  - Why do we trust (our) software?
  - What is Frama-C?
  - Some industrial usage
- **Frama-C/Value**
- **Frama-C/WP**

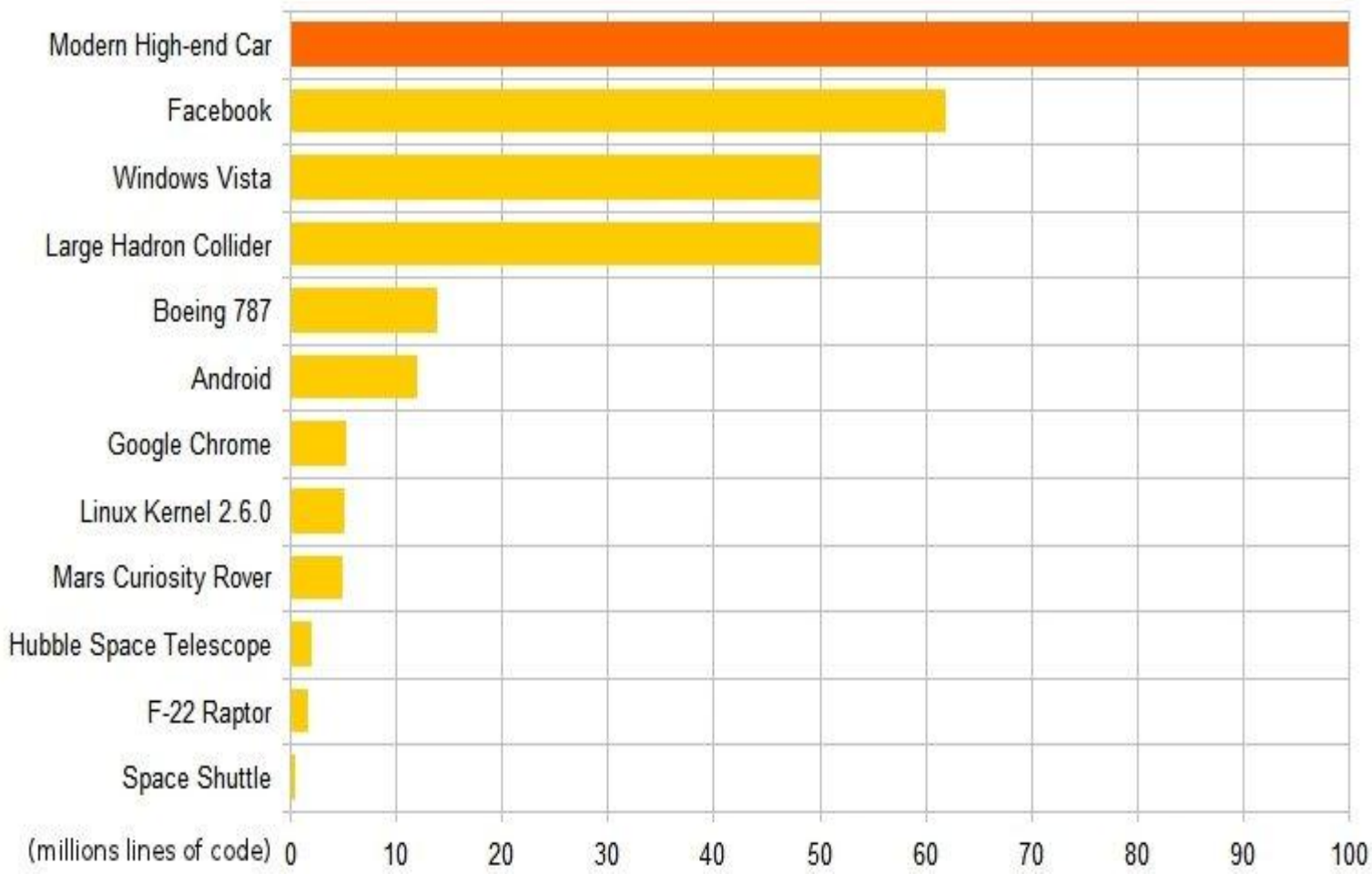
TRUST

WHY DO WE (OUR) SOFTWARE?

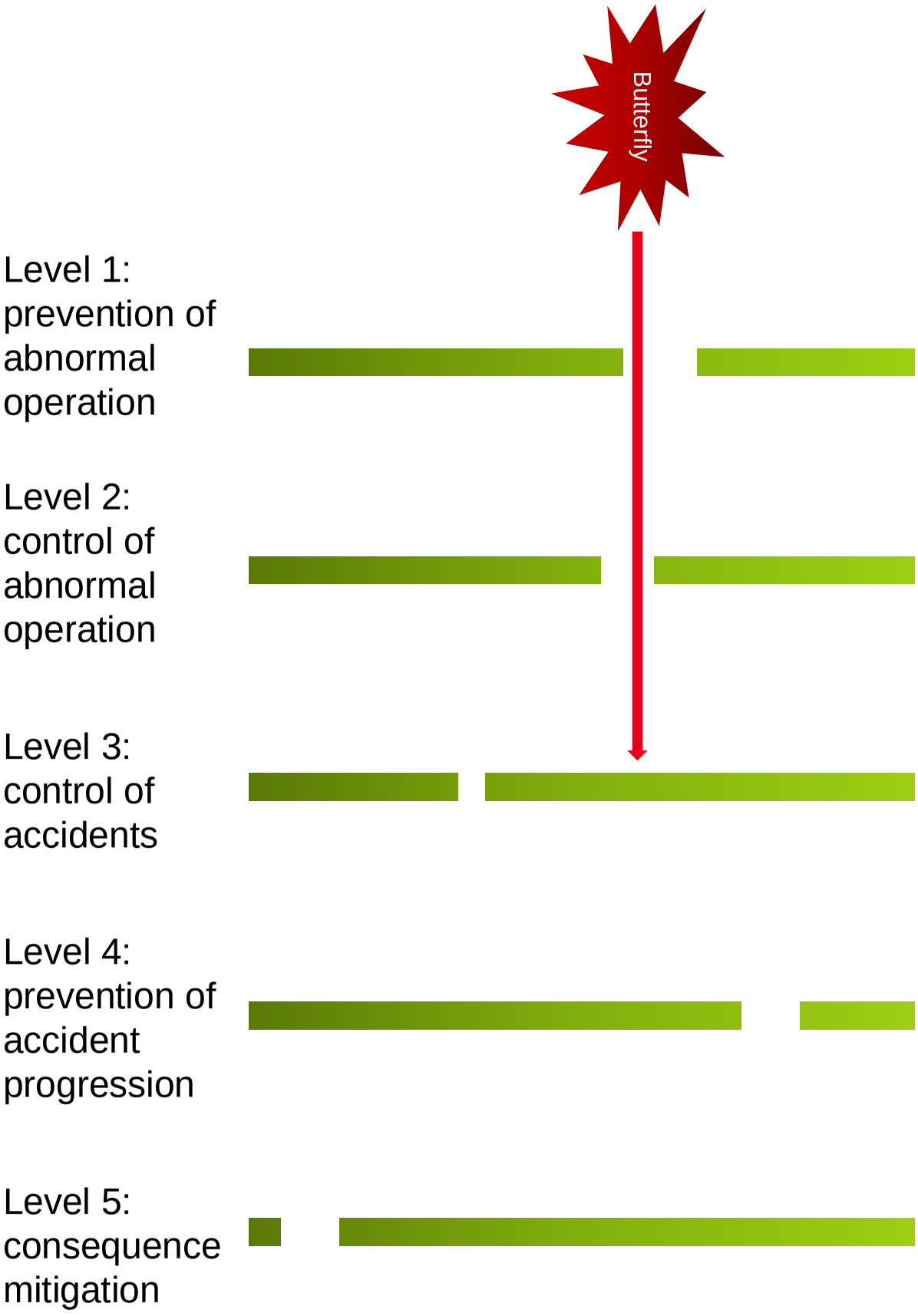
- ✓ Software systems are becoming larger and more complex
- ✓ Life-critical software cannot be permitted to exhibit unexpected behaviors or security vulnerabilities
- ✓ Stringent certification standards require strong guarantees
  - ✓ DO-178B/C for aerospace safety
  - ✓ EN 50128 for rail safety
  - ✓ ISO 26262 for road vehicles (since 2011)
  - ✓ IEC 62304 for medical equipment
  - ✓ CENELEC 61508 reference
  - ✓ Common Criteria EAL7 for security

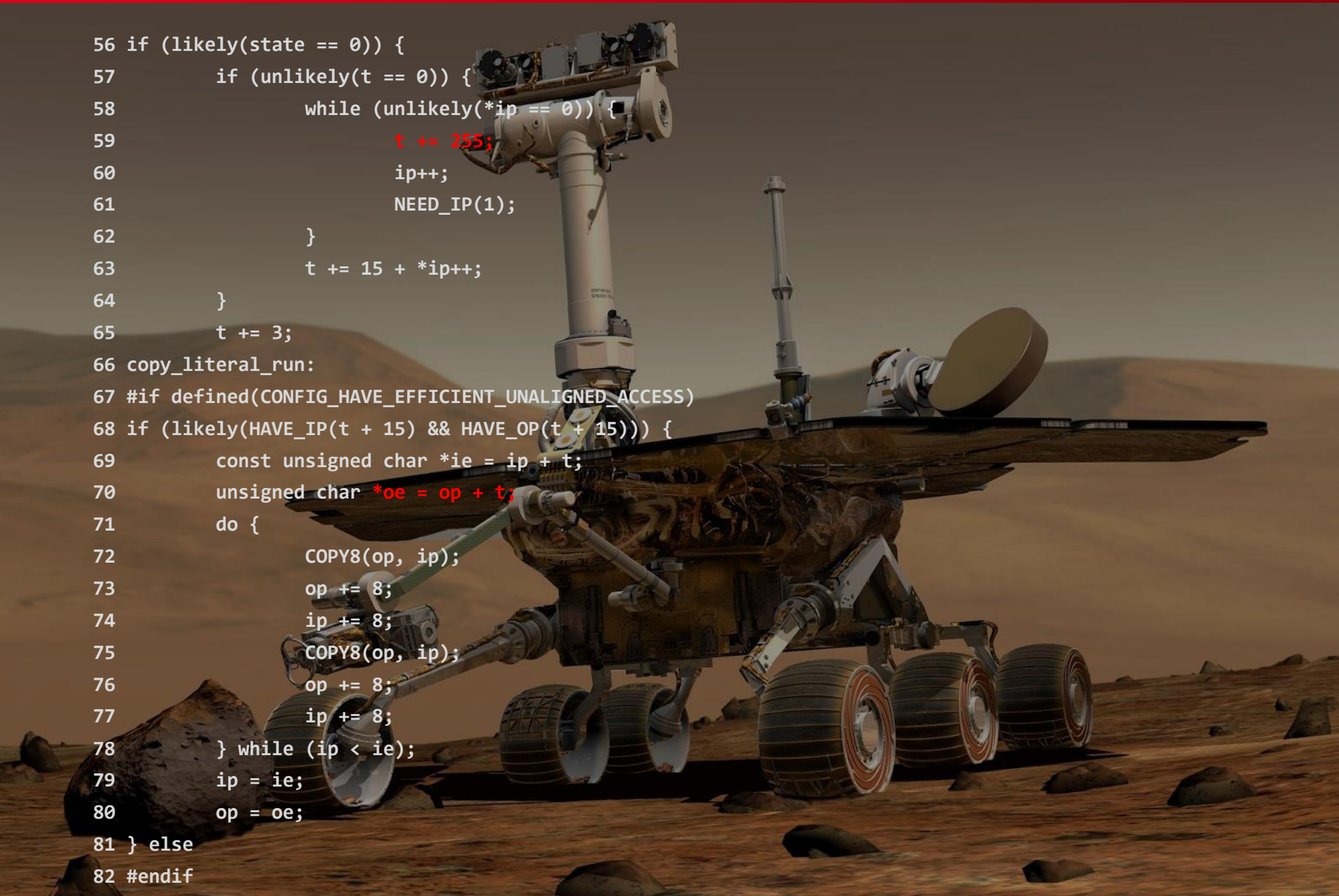


26262
ISO
Common Criteria

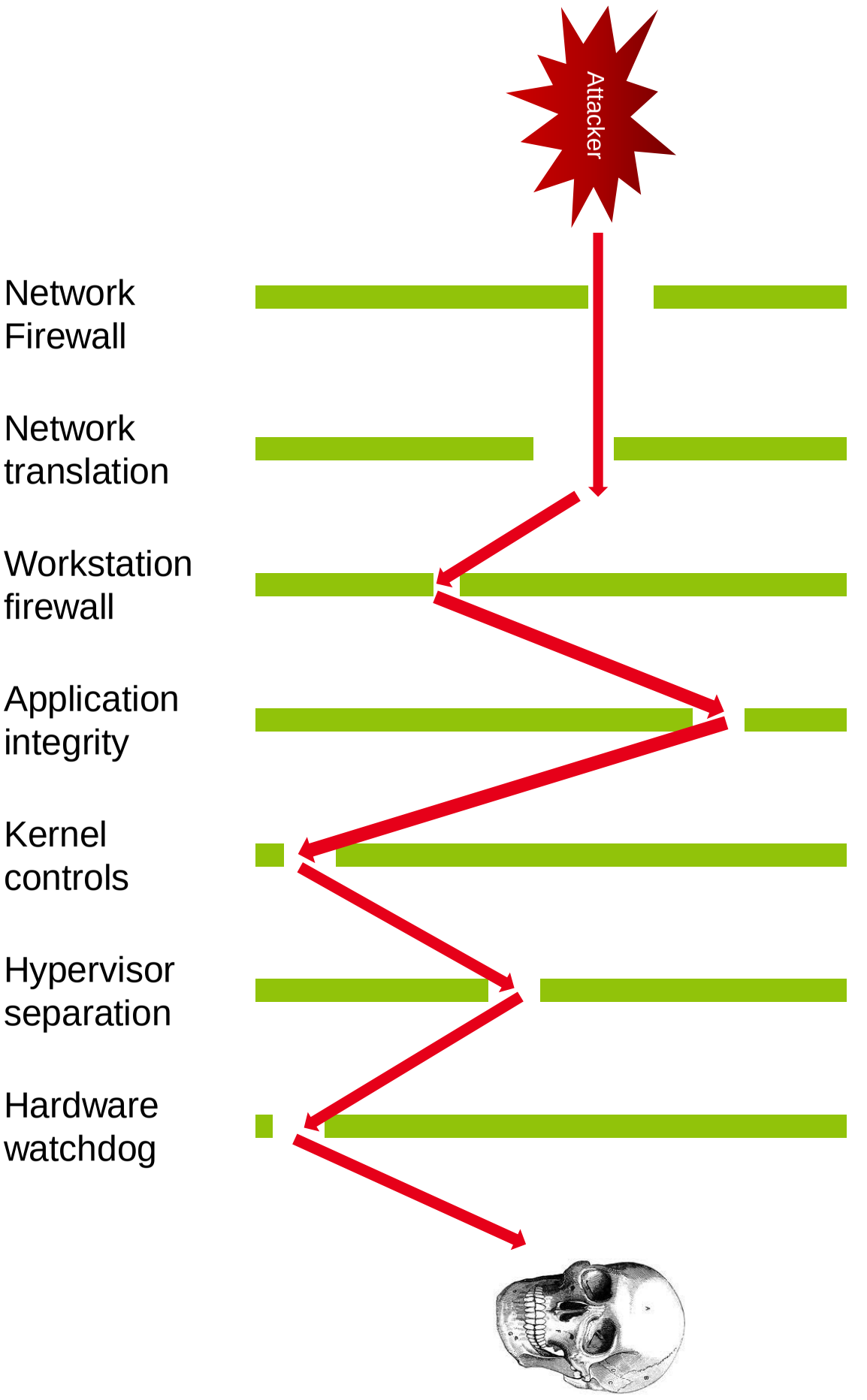


the number of errors partly depends on the software size…


Butterfly
Level 1: prevention of abnormal operation
Level 2: control of abnormal operation
Level 3: control of accidents
Level 4: prevention of accident progression
Level 5: consequence mitigation



```
56 if (likely(state == 0)) {
57         if (unlikely(t == 0)) {
58                 while (unlikely(*ip == 0)) {
59                         t += 255;
60                         ip++;
61                         NEED_IP(1);
62                 }
63                 t += 15 + *ip++;
64         }
65         t += 3;
66 copy_literal_run:
67 #if defined(CONFIG_HAVE_EFFICIENT_UNALIGNED_ACCESS)
68 if (likely(HAVE_IP(t + 15) && HAVE_OP(t + 15))) {
69         const unsigned char *ie = ip + t;
70         unsigned char *oe = op + t;
71         do {
72                 COPY8(op, ip);
73                 op += 8;
74                 ip += 8;
75                 COPY8(op, ip);
76                 op += 8;
77                 ip += 8;
78         } while (ip < ie);
79         ip = ie;
80         op = oe;
81 } else
82 #endif
```


Attacker
Network Firewall
Network translation
Workstation firewall
Application integrity
Kernel controls
Hypervisor separation
Hardware watchdog

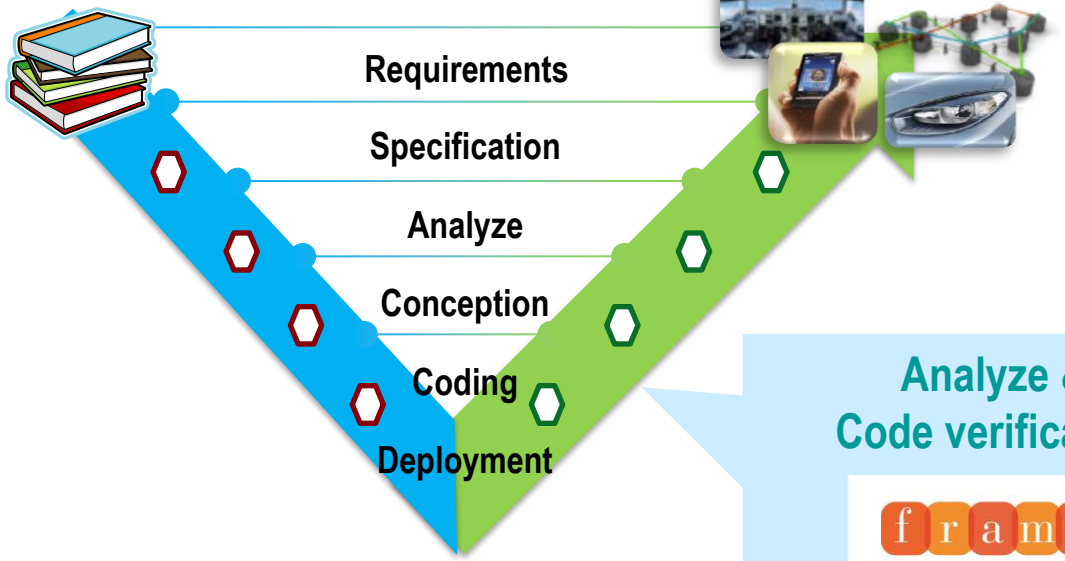
```
2552 #ifndef OPENSSL_NO_HEARTBEATS
2553 int
2554 tls1_process_heartbeat(SSL *s)
2555         {
2556         unsigned char *p = &s->s3->rrec.data[0], *pl;
[…]
2561         /* Read type and payload length first */
2562         hbtype = *p++;
2563         n2s(p, payload);
2564         pl = p;
[…]
2571         if (hbtype == TLS1_HB_REQUEST)
2572                 {
[…]
2583                 /* Enter response type, length and copy payload */
2584                 *bp++ = TLS1_HB_RESPONSE;
2585                 s2n(payload, bp);
2586                 memcpy(bp, pl, payload);
2587                 bp += payload;
2588                 /* Random padding */
2589                 RAND_pseudo_bytes(bp, padding);
2590
2591                 r = ssl3_write_bytes(s, TLS1_RT_HEARTBEAT, buffer,
3 + payload + padding);
2592
2593                 if (r >= 0 && s->msg_callback)
2594                         s->msg_callback(1, s->version,
TLS1_RT_HEARTBEAT,
```

TOOL

FOR HIGH CONFIDENCE

SOFTWARE & SYSTEMS

V&V on the second phase of the cycle



Transfert industriel TRL 4-5-6-7

Maturation TRL 3-4-5

Ressourcement TRL 1-2-3

Analyze & Code verification

frama C Software Analyzers

open source

http://frama-c.com

HOW DO WE TRUST A SOFTWARE?

- **Provide guarantees that it has « no error »**
  - It never crashes
  - It behaves as expected
- **What is the expected behavior?**
  - Specification
- **How to ensure that the runtime behavior is the expected one?**
  - Full compliance of the software wrt its specification
- **Is it possible? At what cost?**

WHAT WOULD BE A PERFERT TOOL?

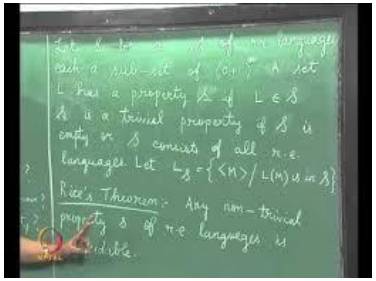
What perfect tool T in order to guarantee that a program P satisfies a specification S?

1. **provide P and S as input to T**
2. **press « enter »: automatic analysis**
3. **T looks at S and T, without executing them: static analysis**
4. **T instantaneously provides an answer**
   - ✓ yes, P satisfies S
   - ✓ no, it doesn't : there is an issue at this program point.
5. **be sure that the tool answer is correct**

Unfortunately, perfection does not exist…

RICE THEOREM (1953)

An automatic exact static analysis is not possible



Any property which is

- extensional (which depends on the program semantics and not on the syntax)
- not trivial (neither always true nor false)

is

- undecidable (any algorithm which decides whether such a property is valid either loops forever or is wrong for an infinity of input programs)

PRAGMATIC SOLUTIONS TO A THEORETICAL ISSUE

Relax (at least) one constraint

- **Test: execute the program in order to find bugs**
  - Most standard industrial practice
  - Not exhaustive: cannot prove the absence of errors
- **Model checking (Clarke & Emerson 81, Queille & Sifakis 82)**
  - Verify a model of the program
  - Compliance of the program wrt its model?

- **Deductive methods (Dijkstra 76)**
  - Mathematical reasoning about the program
  - Not fully automatic

- **Abstract interpretation (Cousot & Cousot 77)**
  - Correct approximation of the program behavior
  - May answer « I don’t know »

FRAMA-C

- developed by **CEA LIST** since 2005 (in collaboration with Inria)
- **platform for the analysis of source code written in C** (ISO C 99)

- Open source (LGPL v2.1)
- Close source extensions for industrial usage

- **several analyzers** inside
- **extensible and collaborative** setting

- both for academic and industrial purposes

Several tools inside a single platform

http://frama-c.com

FRAMA-C: EXTENSIBLE AND COLLABORATIVE PLATFORM

- **plug-in based architecture** *à la* Eclipse
- each analyzer is a plug-in
- each plug-in is connected to the Frama-C **kernel**
  - the kernel provides general services
  - the kernel synthesizes information
- **analyzers may collaborate each other**
  - use results of others analysis
  - exchange formal ACSL properties to be verified
  - **ACSL** : *langua franca* between analyzers

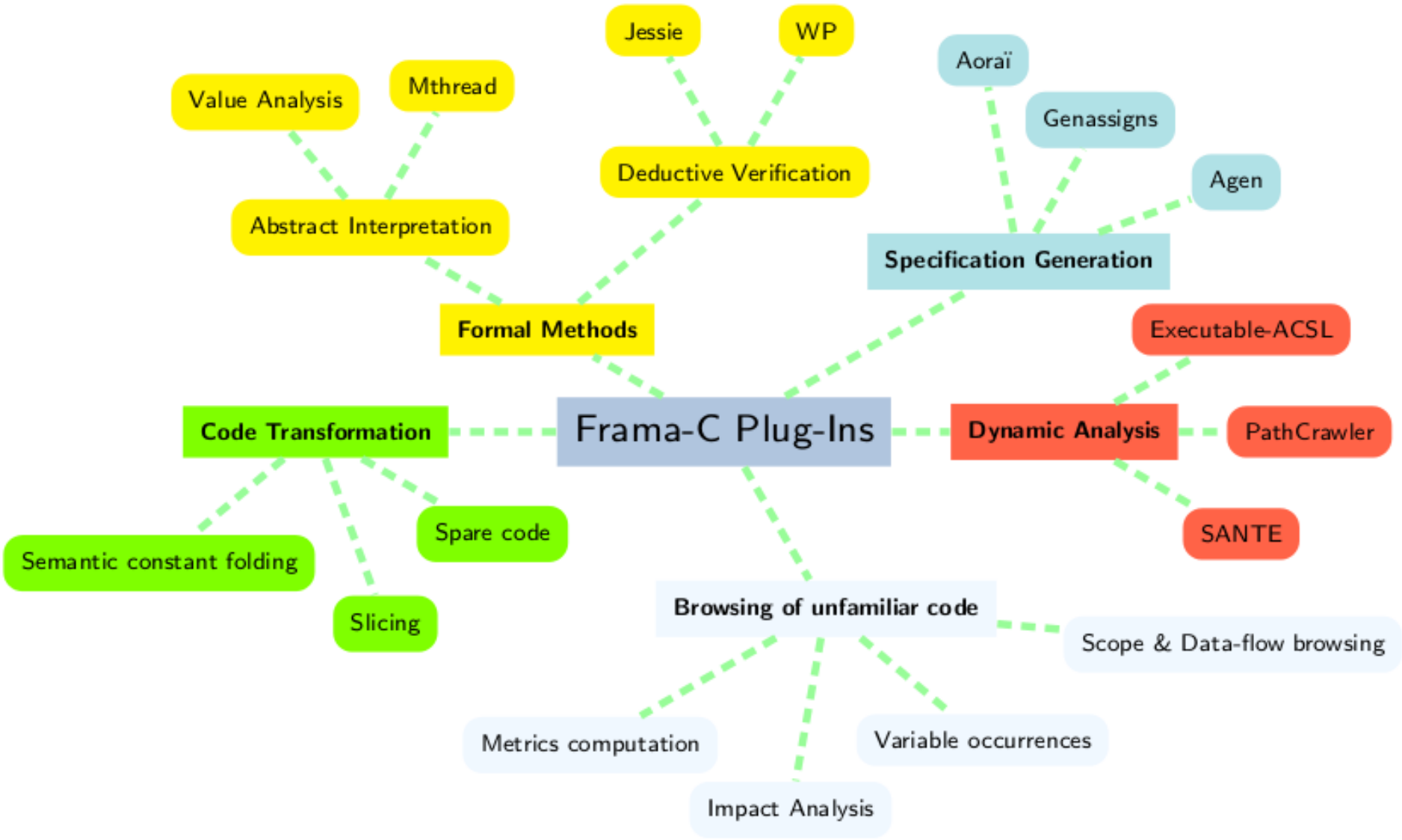
FRAMA-C: DEVELOPMENT PLATFORM

- developed in **OCaml** (>> 100 kloc)
- based on **Cil** (C Intermediate Langage, Berkeley)

- **library dedicated to code analysis of C code**

Development of plug-ins by third party

- **powerful low-cost analyzer**
- **extension** of existing analyzers
- experimentation platform
- dedicated plug-ins for **specific tasks** (e.g. verifying coding rules)


Jessie
WP
Aoraï
Value Analysis
Mthread
Genassigns
Deductive Verification
Agen
Abstract Interpretation
Specification Generation
Formal Methods
Executable-ACSL
Code Transformation
Frama-C Plug-Ins
Dynamic Analysis
PathCrawler
Spare code
Semantic constant folding
SANTE
Slicing
Browsing of unfamiliar code
Scope & Data-flow browsing
Metrics computation
Variable occurrences
Impact Analysis

- properties are formalized using unequivocal specifications
- they can be hand-written
- they can be automatically generated
- they can be automatically verified


```
/*@ requires -1000 <= x <= 1000;
    ensures \result >= 0;
    */
```

```
int abs(int x)
{
  int r;
  if (x >= 0)
    r = x;
  else
    r = - x;
  return r;
}
```

```
int abs(int x)
{
  int r;
  if (x >= 0)
    r = x;
  else
    r = - x;
  return r;
}
```

INDUSTRIAL EXAMPLES OF USAGES

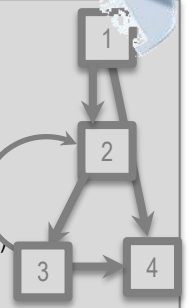
HIGH-QUALITY SOFTWARE AND SYSTEMS

le Analysis :

while (x>=1000) {
x= x-a;
}

: init(x)
: (1000 ≤ x) ∧ (P1 ∨ P3)
P3 : P2[x+a]
P4 : (x<1000) ∧ (P1 ∨ P3)

Research of pre-conditions for infinite loops
(Threat example) ➔ x ≥ 1000 ∧ a ≤ 0



SAFETY
IEC60880

SAFETY
DO-178C

ANALYZING INTRINSIC FAULTS | SCADASYSTEMS

Can we guarantee the absence of defaults in large system-level code?

- **Pinpoint all runtime errors and help investigate their cause**
- **Structural properties on memory separation and cyclic behaviors.**
- **Using collaborative, automated analyses.**
- **Justification and certification to IEC60880 Class 1**

```
> 100+ kloc
> C source code
> Highest
      certification
      requirements

> 80% code coverage
> 200 alarms
```

VERIFYING PROPERTIES | #AVIONICS

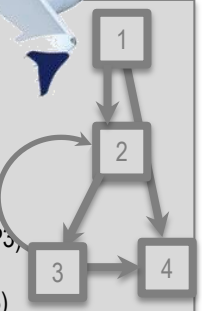
How do we prove that embedded software properties are satisfied?

- **Automate unit proofs on critical code**
- **Using C code interactive verification**
- **A380, A350 & A400M programs**
- **Qualification and certification to DO178B/C level A**

Code Analysis :

```
1 : while (x>=1000) {
2 :   x= x-a;
3 :   }
4 :
```

P1 : init(x)
P2 : (1000 ≤ x) ∧ (P1 ∨ P3)
P3 : P2[x+a]
P4 : (x<1000) ∧ (P1 ∨ P3)



Research of pre-conditions for infinite loops (Threat example) ➔ $x \geq 1000 \wedge a \leq 0$

SAFETY

VERIFYING PROPERTIES | #AVIONICS

- **« Source code matches the data flow and control flow defined in the software architecture »**
  DO178B §6.3.4.b

- **Traditionally performed by code review**

- **Automation objectives**
  - correction (pointers, data alignment)
  - ease of use (push-button)

VERIFYING PROPERTIES | #AVIONICS

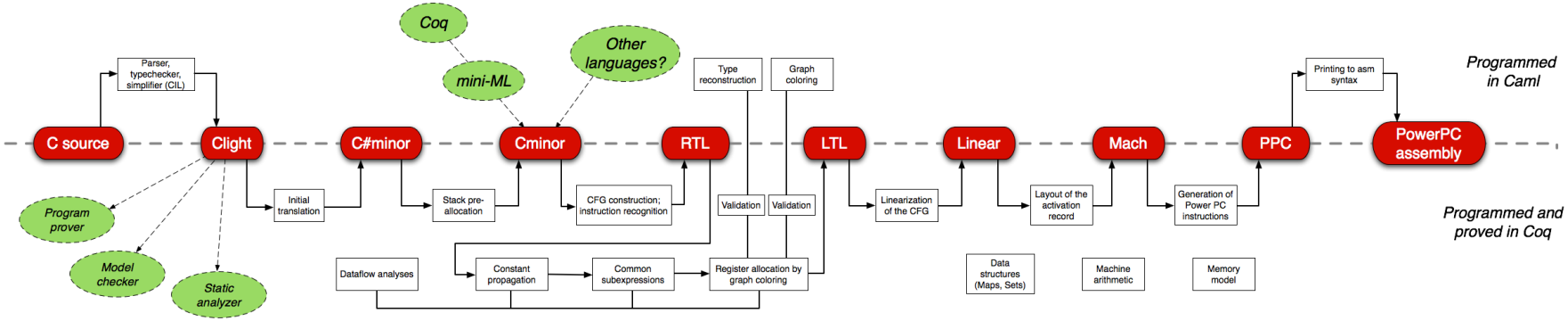
Integration Plugin	Generated ACSL, launch analysis, get results, consolidate and export in reports	Developed by industrials: Airbus SA (and Atos)
Inout, from analysis	Analysis of read/written locations	Standard framework
Semantic analysis	Pointers resolution	
Frama-C kernel	C compilation, Uniform and consistent framework	

FORMAL COMPILER VERIFICATION | #DRAGONS

AIRBUS
AN EADS COMPANY

Can we formally design and implement an optimizing C language compiler?

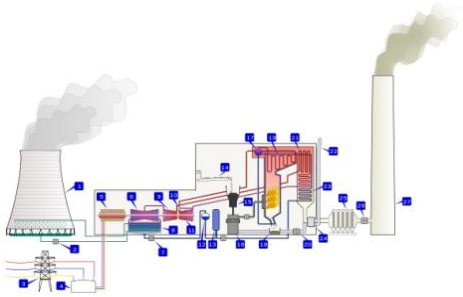
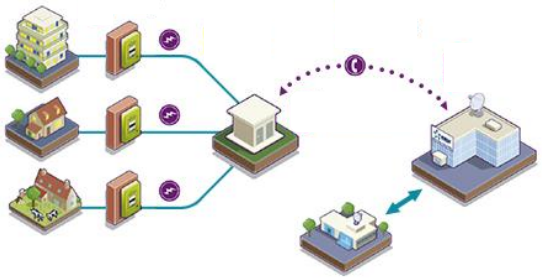
- **Compcert compiler designed and implemented in formal higher-order logics with Coq**
- **MISRA-C 2004, recursive functions, dynamic memory allocation, PPC/ARM/IA32 targets**
- **Justification and certification to DO-178C Level A**



FROM SAFETY

TO SECURITY

Software-intensive systems are spreading widely


SOCIETAL ACCEPTANCE DEMANDS 100% SECURITY GUARANTEES

Formal modeling & validation of software assets

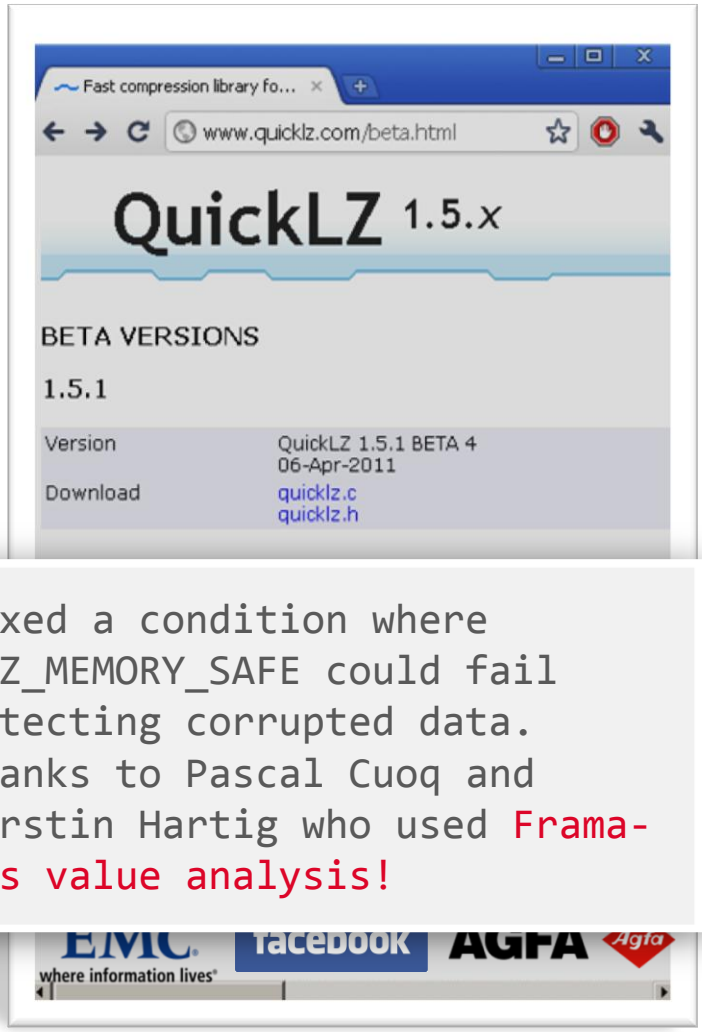
- Frama-C: verify *functional security*, check *data-flow boundaries*, guarantee the absence of *runtime vulnerabilities,* generate *test cases*…

```
2552 #ifndef OPENSSL_NO_HEARTBEATS
2553 int
2554 tls1_process_heartbeat(SSL *s)
2555         {
[…]
2561         /* Read type and payload length first */
2562         hbtype = *p++;
2563         n2s(p, payload);
2564         pl = p;
[…]
2571         if (hbtype == TLS1_HB_REQUEST)
2572                 {
[…]
2583                 /* Enter response type, length and copy payload */
2584                 *bp++ = TLS1_HB_RESPONSE;
2585                 s2n(payload, bp);
2586                 memcpy(bp, pl, payload);
2587                 bp += payload;
2588                 /* Random padding */
2589                 RAND_pseudo_bytes(bp, padding);
2590
2591                 r = ssl3_write_bytes(s, TLS1_RT_HEARTBEAT, buffer,
3 + payload + padding);
2592
2593                 if (r >= 0 && s->msg_callback)
2594                         s->msg_callback(1, s->version,
TLS1_RT_HEARTBEAT,
2595                                 buffer, 3 + payload + padding,
```

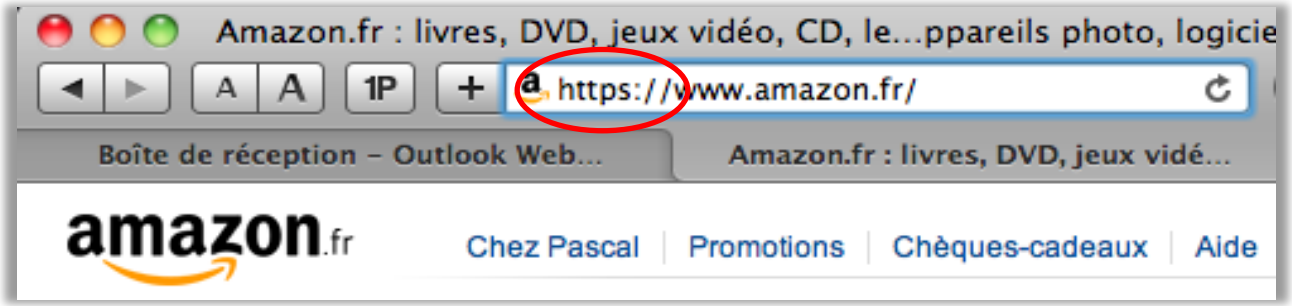
DETECTING SECURITY FLAWS | COTSCOMPRESSIONLIBRARY

How do we reach the sophisticated "last vulnerabilities"?

- **Detect all occurrences of a given category of vulnerabilities.**
- **Using automated code analyses**
- **Handling general-purpose code constructs**
- **Ongoing analysis of the normative context**



VERIFICATION OF POLAR SSL | COTSCRYPTOLIBRARY



POLAR SSL

TRUST IN SOFT

TOOL EXPOSITION & EVALUATION

NIST National Institute of Standards and Technology U.S. Department of Commerce

TRUST IN SOFT

ADIT MINISTÈRE DES AFFAIRES ÉTRANGÈRES Liberté • Égalité • Fraternité RÉPUBLIQUE FRANÇAISE

Are software analysis tools as exhaustive as they claim?

- **NIST's Ockham Criteria provides "known good" and "known bad" code**
- **Evaluated on the Juliet Test Suite – 27000 testcases**
- **Only tool able to satisfy the criteria in 2014**
- **Several bugs found in the Juliet benchmark**

```
<weakness id="2958">
<name>invalid memory access</name>
<location
path="synthetic/testcases/CWE126_Buffer_Over
read/s02/CWE126_Buffer_Overread__malloc_wcha
r_t_loop_03.c" line="70">
</location>
<grade severity="4"/>
<output><textoutput><![CDATA[../ppc/share/li
bc/wchar.c:32:[kernel] warning: out
of bounds write. assert \valid(tmp);
                  stack: wmemset ::
testcases/CWE126_Buffer_Overread/s02/CWE126_
Buffer_Overread__malloc_wchar_t_loop_03.c:70
<-
                           goodG2B1 ::
testcases/CWE126_Buffer_Overread/s02/CWE126_
Buffer_Overread__malloc_wchar_t_loop_03.c:12
3 <-

CWE126_Buffer_Overread__malloc_wchar_t_loop_
03_good
]]></textoutput></output></weakness>
```

TRUST IN SOFT

Frama-C for software safety and security

www.trust-in-soft.com

SOFTWARE DEVELOPERS

- Industrial support
- Commercial licenses
- Preinstalled workstations

SOFTWARE INTEGRATORS

Off-the-shelf validation kits for common open-source packages

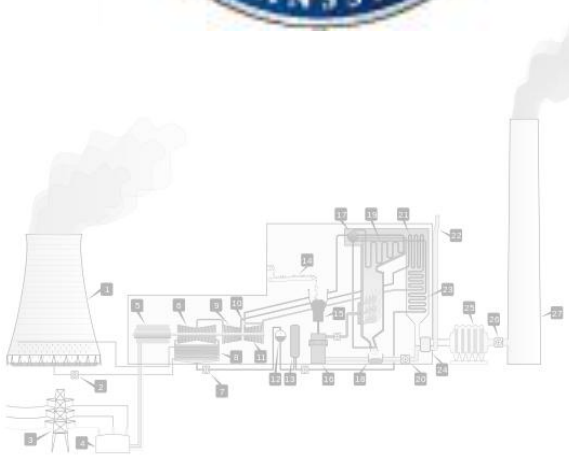
SERVICE PROVIDERS

Dedicated affiliate programs

CYBERSECURITY STANDARDISATION

What is the state of the art in software analysis?

- **Guarantee the absence of runtime errors such as buffer overflows or invalid pointers**
- **Verify that an implementation adheres to a formal security model**
- **Impact analysis, monitor insertion, etc.**



NEXT

DECADE

TECHNOLOGIES

RUNTIME MONITORING AND VERIFICATION

Is it possible to toughen runtime checks in dynamic and compositional systems?

- **Automate monitor generation from formal specifications**
- **Benefit from static analyses to infer specifications and minimize overhead**
- **Use in conjunction with hardware enablers**

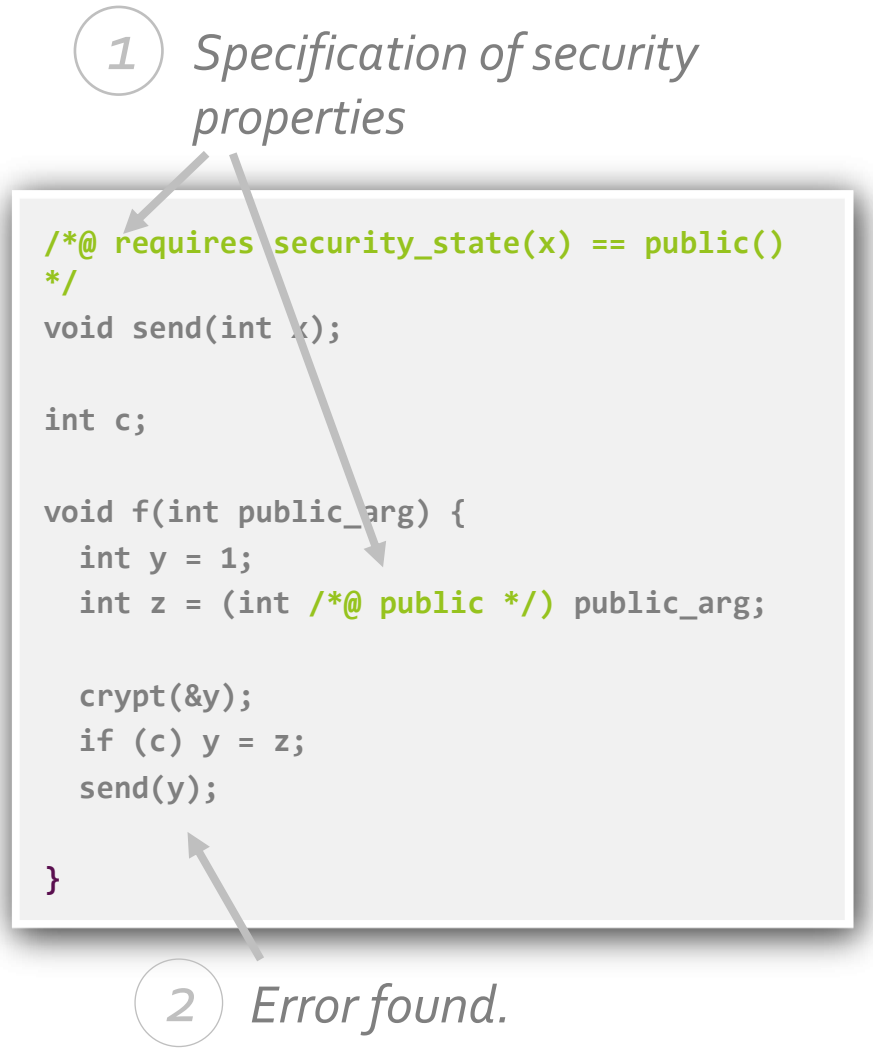
```
int div (int x, int y) {
  // make sure *p != 0;
  return x / *p;
}
```

```
int div (int x, int y) {
  if (!is_valid(p)
      || *p==0)
    e_acsl_fail();
  return x / *p;
}
```

ADVANCED VALIDATION OF A SET OF INFORMATION FLOW PROPERTIES

Can we build on existing analysis tools to specify and verify custom privacy properties?

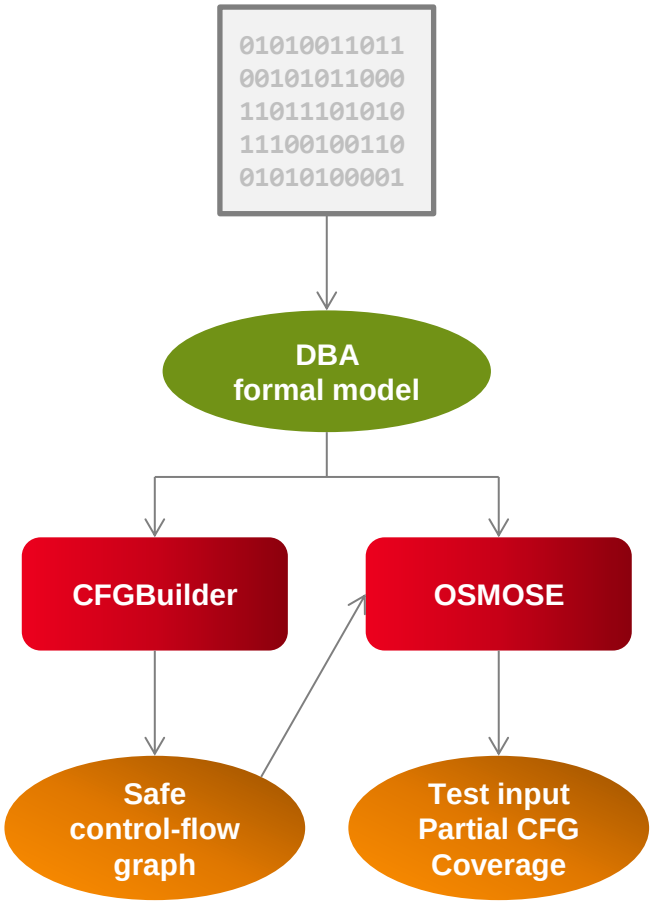
- **Specification and verification of non-interference properties**
- **Mixed static / dynamic techniques**
- **Quantitative information flow analysis at TRL2**



MACHINE CODE SECURITY ANALYSIS

How much can we check when source code isn't an option?

- Intermediate language for machine code analysis (DBA)
- Safe control-flow graph reconstruction based on advanced refinement techniques
- Test data generation through dynamic symbolic execution

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IRSN
Schneider Electric
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Rolls-Royce
ESTEREL Technologies
Atos
Trusted Labs
RENAULT
e-rsb
intel
Adelard
SIEMENS
Valeo
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