Analyse et Conception Formelles

Lesson 7

–

Program verification methods

Outline

1. Testing
2. Model-checking
3. Assisted proof
4. Static Analysis
5. A word about protoypes/models, accuracy, code generation

Disclaimer

Theorem 1 (Rice, 1953)

Any nontrivial property about the language recognized by a Turing machine is undecidable.

“The more you prove the less automation you have”

The basics

Definition 2 (Specification)

A complete description of the behavior of a software.

Definition 3 (Oracle)

An oracle is a *mechanism* determining whether a test has passed or failed, w.r.t a specification.

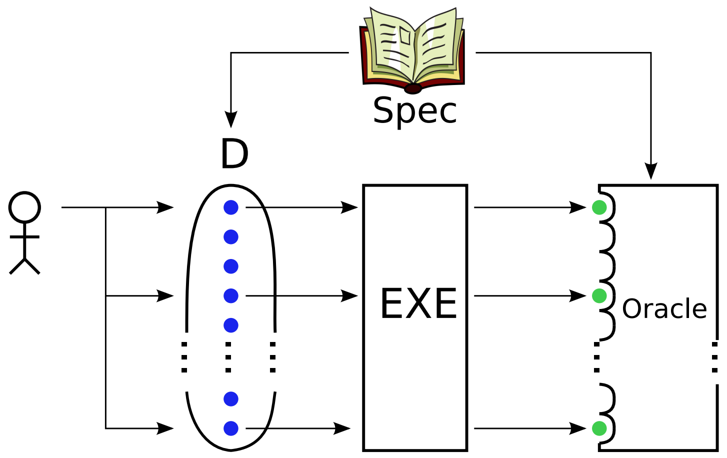
Definition 4 (Domain (of Definition))

The set of all possible inputs of a program, as defined by the specification.

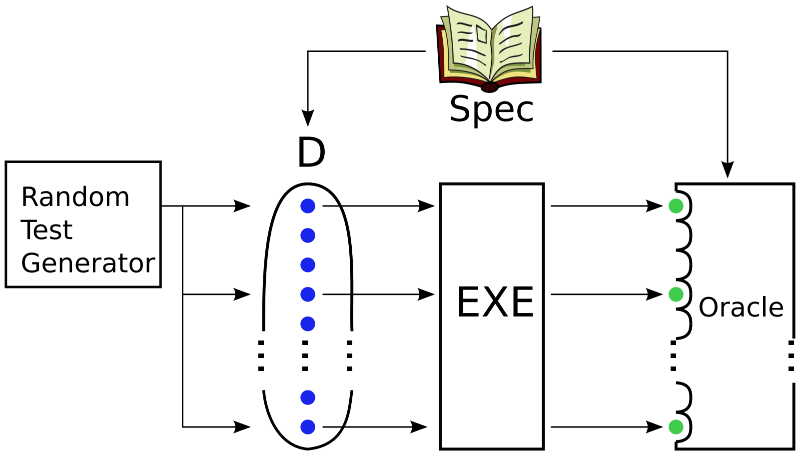
Notations

Spec	the specification
Mod	a formal model or formal prototype of the software
Source	the source code of the software
EXE	the binary executable code of the software
D	the domain of definition of the software
Oracle	an oracle
$D^{\#}$	an abstract definition domain
$Source^{\#}$	an abstract source code
$Oracle^{\#}$	an abstract oracle

Testing principles

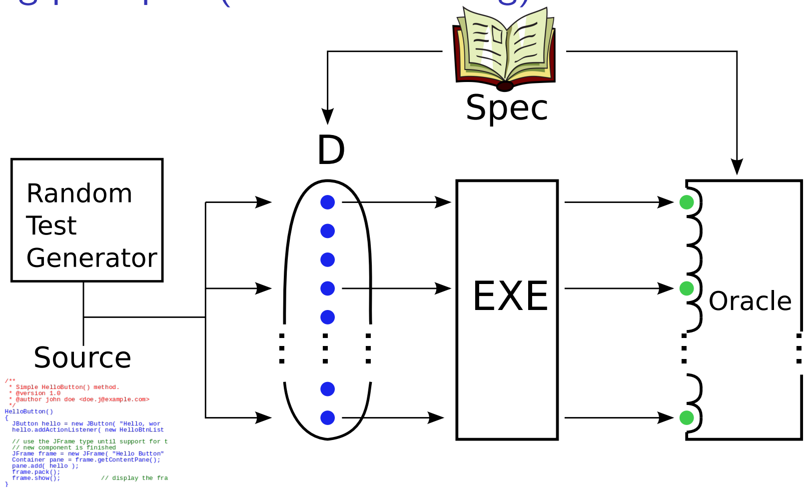


Testing principles (random generators)



This is what Isabelle/HOL `quickcheck` does (and TP4Bis)

Testing principles (white box testing)



```
/**
 * Simple HelloButton() method.
 * @version 1.0
 * @author john doe <doe.j@example.com>
 */
HelloButton()
{
  JButton hello = new JButton( "Hello, wor
  hello.addActionListener( new HelloBtnList

  // use the JFrame type until support for t
  // new component is finished
  JFrame frame = new JFrame( "Hello Button"
  Container pane = frame.getContentPane();
  pane.add( hello );
  frame.pack();
  frame.show();          // display the fra
}
```

Definition 5 (Code coverage)

The degree to which the source code of a program has been tested, *e.g.* a *statement coverage* of 70% means that 70% of all the statements of the software have been tested at least once.

Demo of white box testing in Evosuite

Objective: cover 100% of code (and raised exceptions)

Example 6 (Program to test with Evosuite)

```
public static int Puzzle(int[] v, int i){
  if (v[i]>1) {
    if (v[i+2]==v[i]+v[i+1]) {
      if (v[i+3]==v[i]+18)
         throw new Error("hidden bug!");
      else return 1;}
    else return 2;}
 else return 3;
}
```

Demo of white box testing in Evosuite

Generates tests for all branches (1, 2, 3, null array, hidden bug, etc)

One of the **generated** JUnit test cases:

```
@Test(timeout = 4000)
public void test5()  throws Throwable  {
    int[] intArray0 = new int[18];
    intArray0[1] = 3;
    intArray0[3] = 3;
    intArray0[4] = 21;       // an array raising hidden bug!

    try {
      Main.Puzzle(intArray0, 1);
      fail("Expecting exception: Error");
    } catch(Error e) {
       verifyException("temp.Main", e);
    }
}
```

Testing, to sum up

Strong and weak points

- \+ Done on the code ⟶ Finds real bugs!
- \+ Simple tests are easy to guess
- − Good tests are not so easy to guess! (Recall TP0?)
- \+ Random and white box testing automate this task. May need an oracle: a formula or a reference implementation.
- − Finds bugs but cannot prove a property
- \+ Test coverage provides (at least) a metric on software quality

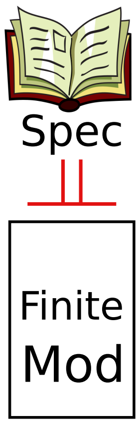
Some tool names

Klee, SAGE (Microsoft), PathCrawler (CEA), Evosuite, many others . . .

One killer result

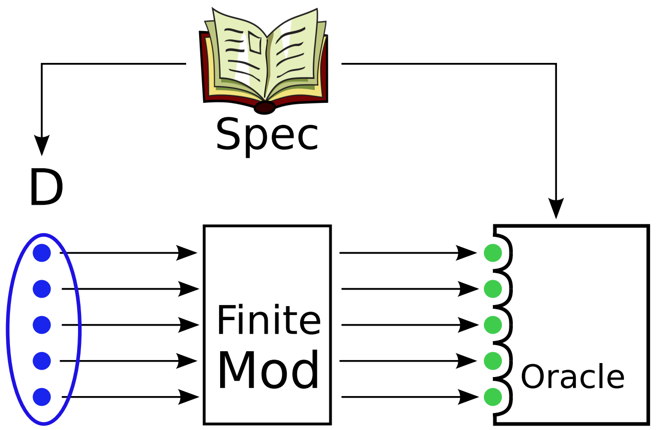
SAGE (running on 200 PCs/year) found 1/3 of security bugs in Windows 7
`https://www.microsoft.com/en-us/security-risk-detection/`

Model-checking principles



Where $\models$ is the usual logical consequence. This property is not shown by doing a logical proof but by checking (by computation) that ...

Model-checking principles (II)



Where D, Mod and Oracle are finite.

Model-checking principle explained in Isabelle/HOL

Automaton `digiCode.as` and Isabelle file `cm7.thy`

Exercise 1

Define the lemma stating that whatever the initial state, typing A,B,C leads execution to Final state.

Exercise 2

Define the lemma stating that the only possibility for arriving in the Final state by typing three letters is to have typed A,B,C.

Model-checking, to sum-up

Strong and weak points

- \+ Automatic and efficient
- \+ Can find bugs and prove the property
- – For finite models only (*e.g* not on source code!)
- \+ Can deal with huge finite models (10^{120} states)
  More than the number of atoms in the universe!
- \+ Can deal with finite abstractions of infinite models *e.g.* source code
- – Incomplete on abstractions (but can find real bugs!)

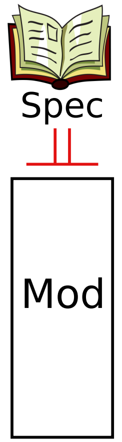
Some tool names

SPIN, SMV, (bug finders) CBMC, SLAM, ESC-Java, Java path finder, . . .

One killer result

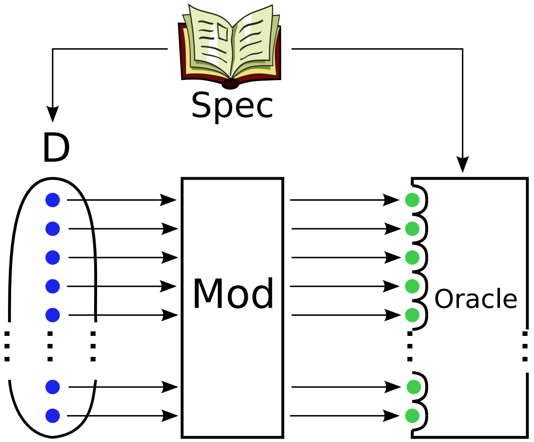
INTEL processors are commonly model-checked

Assisted proof principles



Where $\models$ is the usual logic consequence. This is proven directly on formulas Mod and Spec. This proof guarantees that...

Assisted proof principles (II)



Where D, Mod, Oracle can be infinite.

Assisted proof, to sum-up

Strong and weak points

- + Can do the proof or find bugs (with counterexample finders)
- + Proofs can be certified
- – Needs assistance
- – For models/prototypes only (not on source nor on EXE)
- + Proof holds on the source code if it is generated from the prototype

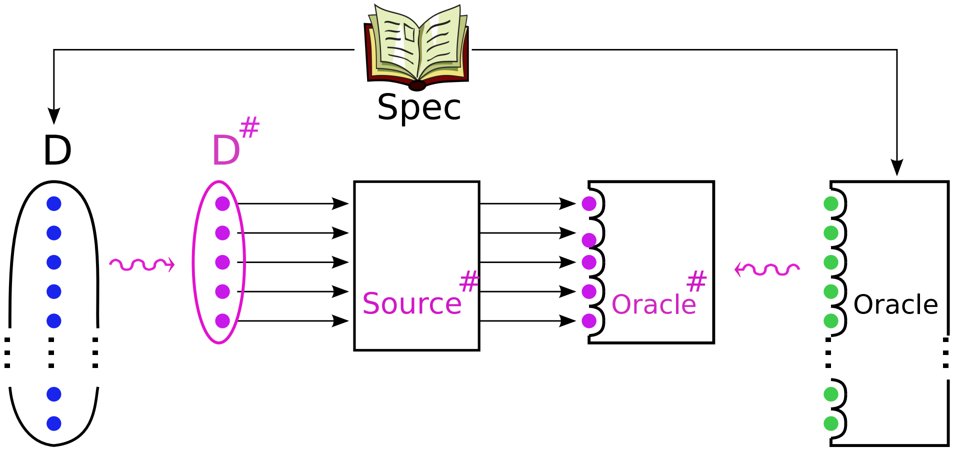
Some tool names

B, Coq, Isabelle/HOL, ACL2, PVS, . . . Why, Frama-C, . . .

One killer result

CompCert certified C compiler

Static Analysis principles



Where abstraction $\rightsquigarrow$ is a correct abstraction

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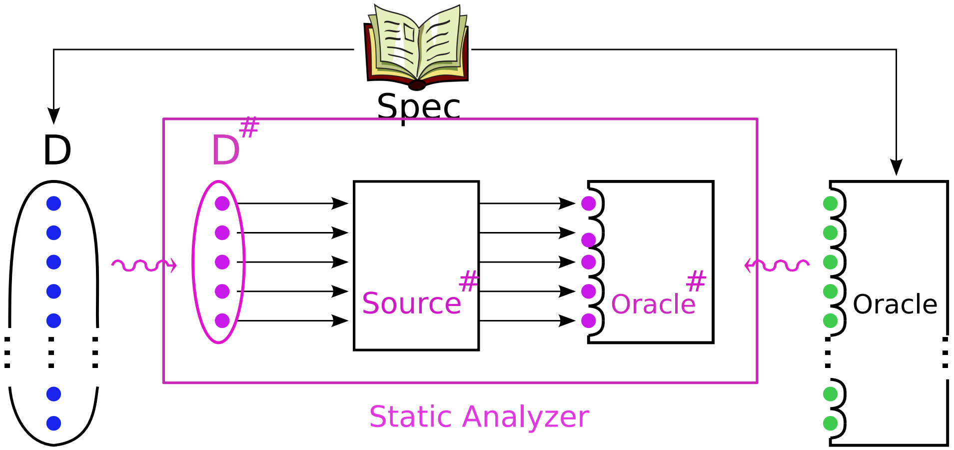
Static Analysis principles (II)



Where abstraction $\rightsquigarrow$ is a correct abstraction

Static Analysis principles – Abstract Interpretation (III)

The abstraction '$\rightsquigarrow$' is based on the abstraction function abs:: D ⇒ $D^{\#}$

Depending on the verification objective, precision of abs can be adapted

Example 7 (Some abstractions of program variables for D=int)

(1) abs:: `int` ⇒ $\{\bot, \top\}$ where $\bot \equiv$ "undefined" and $\top \equiv$ "any `int`"

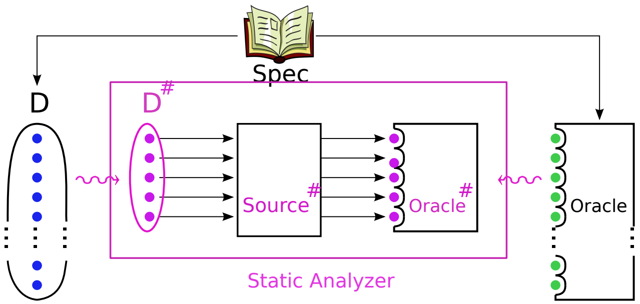
(2) abs:: `int` ⇒ $\{\bot$, `Neg`, `Pos`, `Zero`, `NegOrZero`, `PosOrZero`, $\top\}$

(3) abs:: `int` ⇒ $\{\bot\} \cup$ Intervals on $\mathbb{Z}$

Example 8 (Program abstraction with abs (1), (2) and (3))

	(1)	(2)	(3)
`x:= y+1;`	x=⊥	x=⊥	x=⊥
`read(x);`	x=⊤	x=⊤	x=]-∞;+∞[
`y:= x+10`	y=⊤	y=⊤	y=]-∞;+∞[
`u:= 15;`	u=⊤	u=Pos	u=[15;15]
`x:= |x|`	x=⊤	x=PosOrZero	x=[0;+∞[
`u:= x+u;`	u=⊤	u=Pos	u=[15;+∞[

Static Analysis: proving the correctness of the analyzer



- Formalize semantics of Source language, *i.e.* formalize an `eval`
- Formalize the oracle: `BAD` predicate on program states
- Formalize the abstract domain $D^{\#}$
- Formalize the static analyser `SAn`:: program ⇒ bool
- Prove correctness of `SAn`: $\forall$ **P**. `SAn`(**P**) $\longrightarrow$ ($\neg$ `BAD`(`eval`(**P**)))
- ... Relies on the proof that $\rightsquigarrow$ is a correct abstraction

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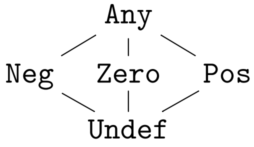
Static Analysis principle explained in Isabelle/HOL

To abstract `int`, we define `absInt` as the abstract domain ($D^{\#}$):

```
datatype absInt= Neg|Zero|Pos|Undef|Any
```



Remark 1

Have a look at the concretization function (called `concrete`*) defining sets of integers represented by abstract elements* `Neg`, `Zero`, *etc.*

Exercise 3

Define the function `absPlus`:: `absInt` ⇒ `absInt` ⇒ `absInt` *(noted* $+^{\#}$*)*

Exercise 4 (Prove that $+^{\#}$ is a correct abstraction of $+$)

$x \in \texttt{concrete}(x^a) \wedge y \in \texttt{concrete}(y^a) \longrightarrow (x+y) \in \texttt{concrete}(x^a +^{\#} y^a)$

Static Analysis, to sum-up

Strong and weak points

+ Can prove the property
+ Automatic
+ On the source code
– Not designed to find bugs

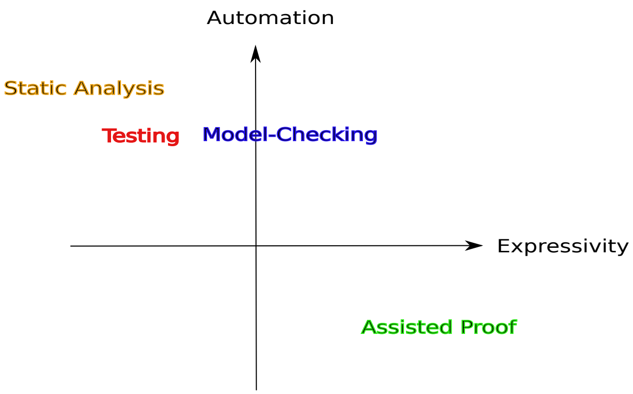
Some tool names

Astree (Airbus), Polyspace, Sawja, Infer (Facebook)...

One killer result

Astree was used to successfully analyze 10^6 lines of code of the Airbus A380 flight control system

To sum-up on all presented techniques



Automation

Static Analysis

Testing

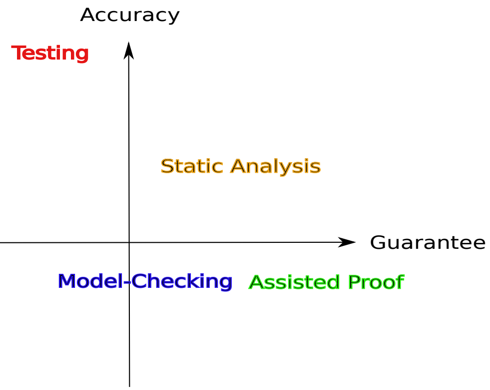
Model-Checking

Expressivity

Assisted Proof

- Some properties are too complex to be verified using a static analyzer
- Testing can only be used to check finite properties
- Model-checking deals only with finite models (to be built by hand)
- Static analysis is always fully automatic

To sum-up on all presented techniques



Accuracy

Testing

Static Analysis

Guarantee

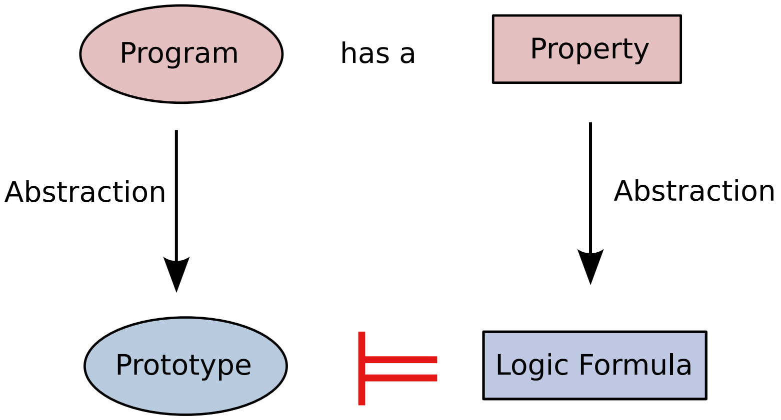
Model-Checking

Assisted Proof

- Testing works on EXE, Static analysis on source code, others on models/prototypes
- Model-checking, assisted proof and static analysis have a similar guarantee level except that assisted proofs can be certified

A word about models/prototypes

Program verification using "formal methods" relies on:



Program

has a

Property

Abstraction

Abstraction

Prototype

$\models$

Logic Formula

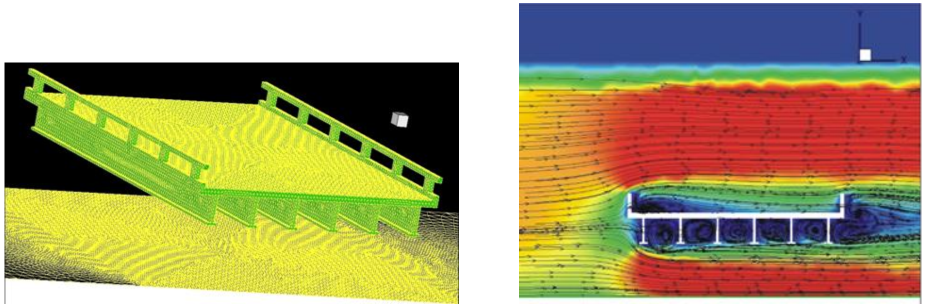
This is the case for model-checking and assisted proof.

Testing prototypes is a common practice in engineering

It is crucial for early detection of problems! Do you know Tacoma bridge?

Testing prototypes is an engineering common practice (II)

More and more, prototypes are mathematical/numerical models



If the prototype is accurate: any detected problem is a real problem!

Problem on the prototype ⟶ Problem on the real system

But in general, we do not have the opposite:

No problem on the prototype $\not\longrightarrow$ No problem on the real system

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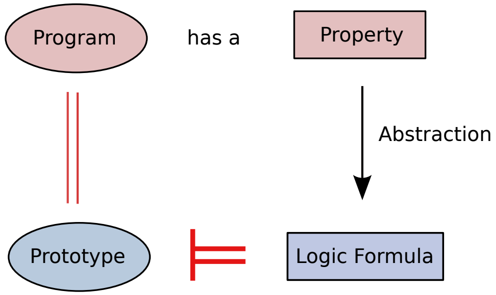
Why code exportation is a great plus?

Code exportation produces the program from the model itself!



Program

has a

Property

Abstraction

Prototype

$\models$

Logic Formula

Thus, we here have a great bonus: [TP5, TP67, TP89, CompCert]

No problem on the prototype ⟶ No problem on the real system

If the exported program is not efficient enough it can, at least, be used as a reference implementation (an oracle) for testing the optimized one.

About "Property $\xrightarrow{\text{Abstraction}}$ Logic formula"

This is the only remaining difficulty, and this step is necessary!

Back to TP0, it is very difficult for two reasons:

1. The "what to do" is not as simple as it seems
    - Many tests to write and what exactly to test?
    - How to be sure that no test was missing?
    - Lack of a concise and precise way to state the property
      Defining the property with a french text is too ambiguous!
2. The "how to do" was not that easy

Logic Formula = factorization of tests

- guessing 1 formula is harder than guessing 1 test
- guessing 1 formula is harder than guessing 10 tests
- guessing 1 formula is not harder than guessing 100 tests
- guessing 1 formula is faster than writing 100 tests (TP0 in Isabelle)
- proving 1 formula is stronger than writing infinitely many tests

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About formal methods and security

You have to use formal methods to secure your software

... because hackers will use them to find new attacks!

Be serious, do hackers read scientific papers?

or use academic stuff?

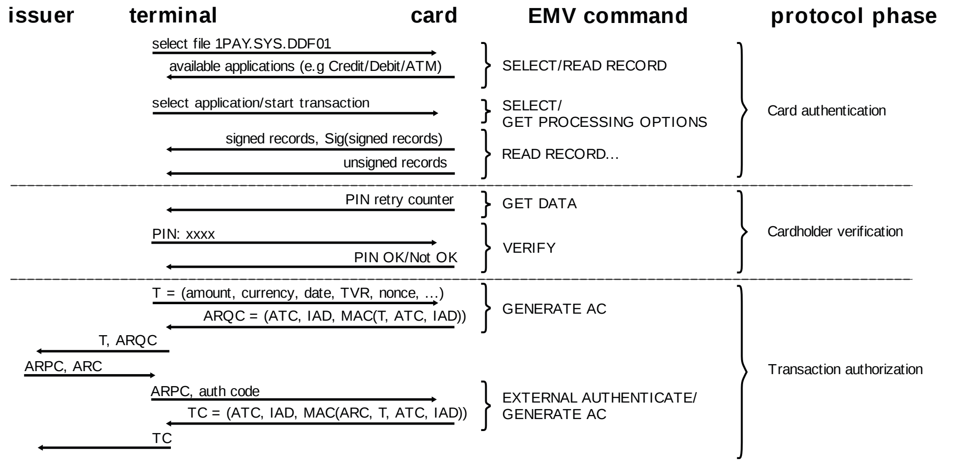
Yes, they do!

Hackers do read scientific papers!

Chip and PIN is Broken

Steven J. Murdoch, Saar Drimer, Ross Anderson, Mike Bond
University of Cambridge
Computer Laboratory
Cambridge, UK

Conference
Security and Privacy
2010
13 pages



issuer **terminal** **card** **EMV command** **protocol phase**

select file 1PAY.SYS.DDF01
available applications (e.g Credit/Debit/ATM)
SELECT/READ RECORD

select application/start transaction
SELECT/
GET PROCESSING OPTIONS

signed records, Sig(signed records)
unsigned records
READ RECORD...

Card authentication

PIN retry counter
GET DATA

PIN: xxxx
PIN OK/Not OK
VERIFY

Cardholder verification

T = (amount, currency, date, TVR, nonce, ...)
ARQC = (ATC, IAD, MAC(T, ATC, IAD))
GENERATE AC

T, ARQC
ARPC, ARC

ARPC, auth code
TC = (ATC, IAD, MAC(ARC, T, ATC, IAD))
EXTERNAL AUTHENTICATE/
GENERATE AC

TC

Transaction authorization

Hackers do read scientific papers!

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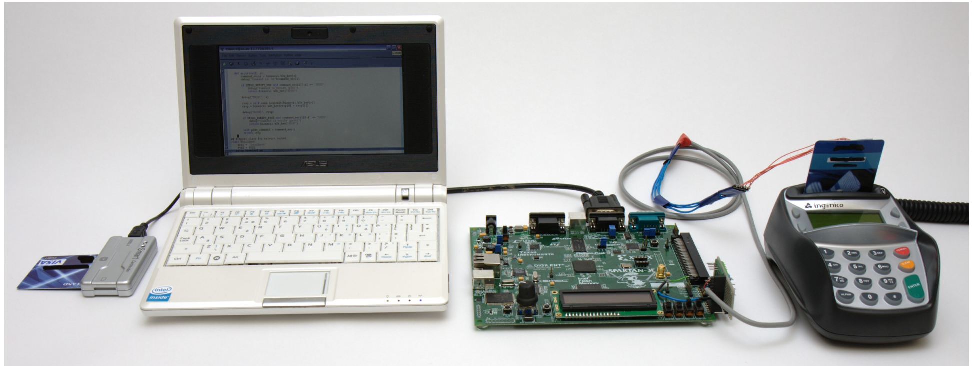
They revealed a weakness in the payment protocol of EMV

They showed how to make a payment with a card without knowing the PIN



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When Organized Crime Applies Academic Results
A Forensic Analysis of an In-Card Listening Device

Houda Ferradi, Rémi Géraud, David Naccache, and Assia Tria

[1] École normale supérieure
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Journal of
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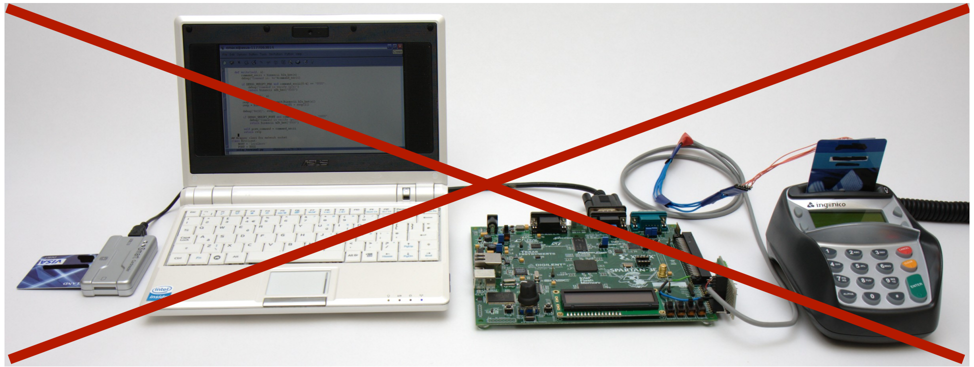
Criminals used the attack of Murdoch & al. but not:



About formal methods and security

You have to use formal methods to secure your software

... because hackers will use them to find new attacks!

(1 formula) + (counter-example generator) ⟶ attack!

- Fuzzing of implementations using model-checking
- Finding bugs (to exploit) using white-box testing
- Finding errors in protocols using counter-example gen. (e.g. TP89)

⟹ You will have to formally prove security of your software!