Formal Methods at Work

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Part I

Where Do We Stand?

Software is omnipresent in everyday life

Today's car: typically 100 processing units, 100 M. lines of code, 600 *Quijotes*, 7.000 programmer years.

Software is omnipresent in everyday life

Plane: computers manage controls, calculate routes, ...

Software is omnipresent in everyday life

Large interconnected systems: independent, isolated, automatic decision making, which must be globally correct.

Software is omnipresent in everyday life

- Cell phones (from O.S. to compression algorithms to user interfaces).
- HDTV (routing, encoding and decoding).
- Buy and sell on the Internet (web interfaces, databases, encryption).
- Stock market (algorithmic trading, high frequency trading).

- √ Managed by extremely complex software.
- √ All of them *critical* to a certain degree.
- √ Some **extremely** critical

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Challenge:

How to develop complex software, with resources that are always limited, assuring that it will work correctly?

How Far Are We from Giving Reasonable Guarantees?

(Only showing some types of problems)

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Defects leave critical military, industrial infrastructure open to hacks (Niagara Framework, linking 11+ million devices in 52 countries).

How Far Are We from Giving Reasonable Guarantees?

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- July 16, 2012: Skype bug sends messages to unintended recipients.
- July 13, 2012: Apple's "in-app purchase" service for iOS bypassed by Russian hacker.
- July 12, 2012: Mountain Lion (Mac OS X version) sends some 64-bit Macs to sleep (related to graphics drivers).
- July 5, 2012: iOS, Mac app crashes linked to botched FairPlay DRM.
- July 7, 2012: Still infected, 300,000 PCs to lose Internet access.
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Just two weeks!!!

The Ariane 5 Incident

Example: effect of a *single* integer overflow.

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From the outside...

- June 4, 1996: After launch, the Ariane 5 rocked exploded.
- This was its maiden voyage.
- It flew for about 37 sec. only in Kourou's sky.
- No injury in the disaster.

Mechanical details

- Normal behavior of the launcher for 36 sec. after lift-off.
- Failure of both Inertial Reference Systems almost simultaneously.
- Strong pivoting of the nozzles of the boosters and Vulcain engine.
- Self-destruction at an altitude of 4000 m. (1000 m. from the pad).

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Forensic analysis

- Both inertial computers failed because of overflow on one variable.
- This caused a software exception and stops these computers.
- These computers sent post-mortem info through the bus.
- Normally the main computer receives velocity info through the bus.
- The main computer was confused and pivoted the nozzles.

But, why?

- The faulty program was working correctly on Ariane 4.
- The faulty program was not tested for A5 (since it worked for A4).
- But the velocity of Ariane 5 is far greater than that of Ariane 4.
- That caused the overflow in one variable.
- The faulty program happened to be **useless** for Ariane 5.

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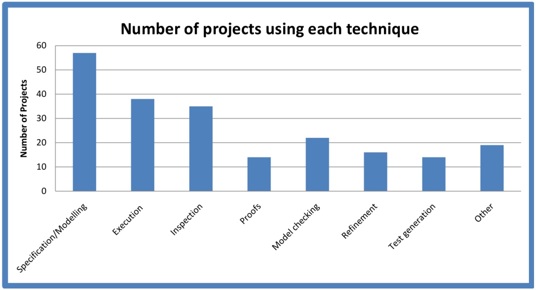
Message

- Does the product conform to specifications?
- Maybe it's important to carry experience in formal methods to industry!
- Is it done?

Formal Methods in Industry

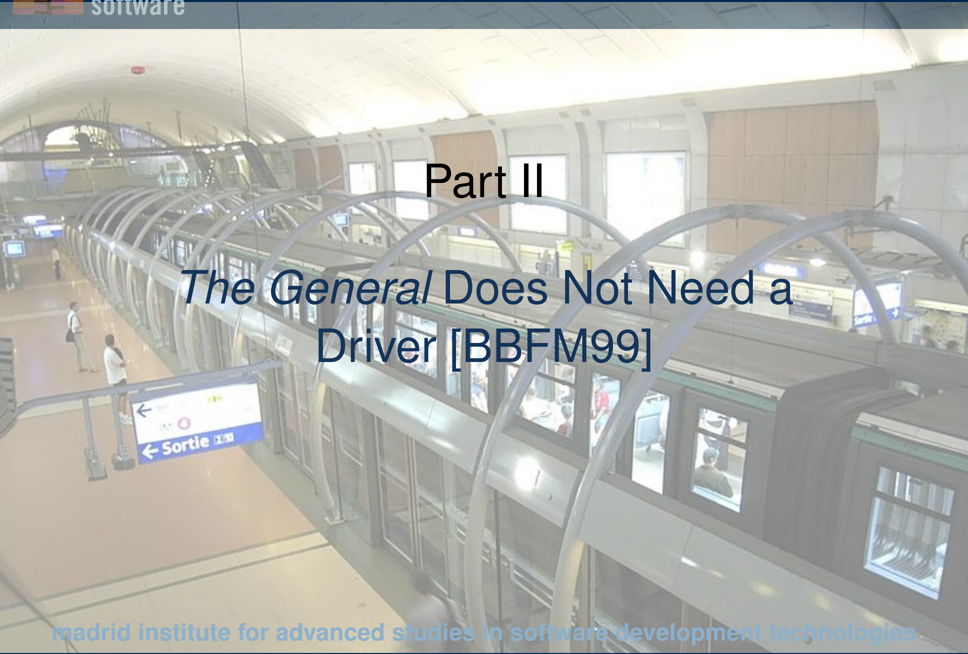
- Actually, yes — at least in some domains, for some types of applications.
- Using many approaches, actually [WLBF09].

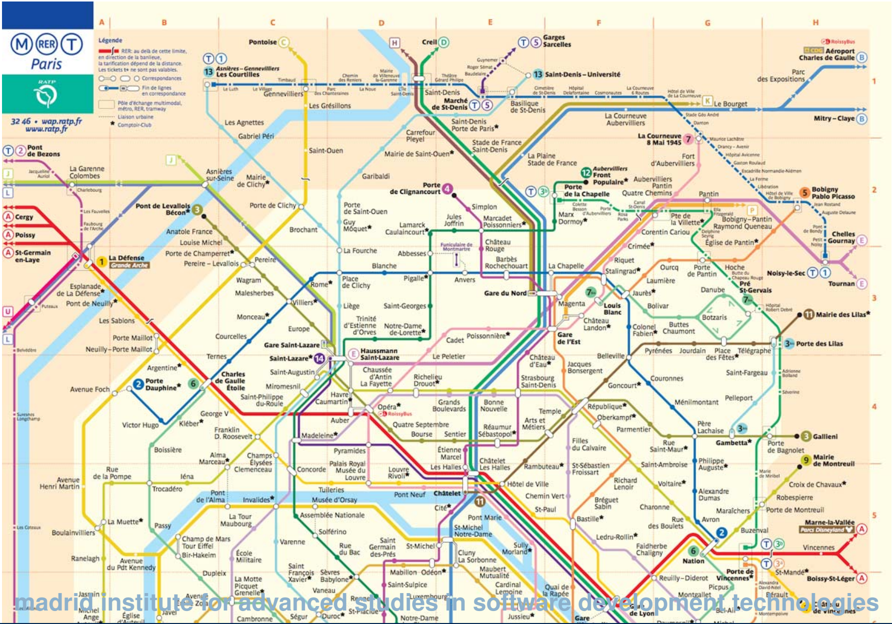


- We will see some examples

Part II

The General Does Not Need a Driver [BBFM99]

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Parc des Expositions
Le Bourget
Mitry – Claye
Gennevilliers
Les Grésillons
Saint-Denis
Marché de St-Denis
Basilique de St-Denis
Les Agnettes
Gabriel Péri
Saint-Ouen
Carrefour Pleyel
Saint-Denis Porte de Paris
Stade de France Saint-Denis
La Plaine Stade de France
La Courneuve Aubervilliers
La Courneuve 8 Mai 1945
Fort d'Aubervilliers
Aubervilliers Front Populaire
Aubervilliers Pantin Quatre Chemins
Bobigny Pablo Picasso
Pont de Bezons
La Garenne Colombes
Asnières sur-Seine
Mairie de Clichy
Mairie de Saint-Ouen
Garibaldi
Porte de Clignancourt
Porte de la Chapelle
Pantin
Cergy
Poissy
St-Germain en-Laye
Pont de Levallois Bécon
Anatole France
Louise Michel
Porte de Champerret
Pereire – Levallois
La Défense Grande Arche
Esplanade de La Défense
Pont de Neuilly
Les Sablons
Porte Maillot
Neuilly – Porte Maillot
Argentine
Porte Dauphine
Charles de Gaulle Étoile
Avenue Foch
Victor Hugo
Kléber
George V
Porte de Clichy
Brochant
Guy Môquet
Porte de Saint-Ouen
Lamarck Caulaincourt
Jules Joffrin
Simplon
Marcadet Poissonniers
Château Rouge
Barbès Rochechouart
La Chapelle
Bobigny – Pantin Raymond Queneau
Église de Pantin
Chelles Gournay
Noisy-le-Sec
Tournan
La Fourche
Abbesses
Blanche
Pigalle
Anvers
Gare du Nord
Stalingrad
Jaurès
Laumière
Ourcq
Porte de Pantin
Hoche
Pré St-Gervais
Wagram
Malesherbes
Villiers
Rome
Place de Clichy
Liège
Saint-Georges
Trinité d'Estienne d'Orves
Notre-Dame de-Lorette
Magenta
Gare de l'Est
Louis Blanc
Château Landon
Colonel Fabien
Bolivar
Botzaris
Buttes Chaumont
Danube
Mairie des Lilas
Porte des Lilas
Monceau
Europe
Courcelles
Gare Saint-Lazare
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Haussmann Saint-Lazare
Ternes
Saint-Augustin
Miromesnil
Saint-Philippe du-Roule
Havre Caumartin
Chaussée d'Antin La Fayette
Richelieu Drouot
Le Peletier
Cadet
Poissonnière
Château d'Eau
Jacques Bonsergent
Belleville
Pyrénées
Jourdain
Place des Fêtes
Télégraphe
Saint-Fargeau
Pelleport
Couronnes
Ménilmontant
Goncourt
Strasbourg Saint-Denis
Bonne Nouvelle
Grands Boulevards
Opéra
Auber
Madeleine
Quatre Septembre
Bourse
Sentier
Réaumur Sébastopol
Arts et Métiers
Temple
République
Oberkampf
Parmentier
Père Lachaise
Gambetta
Gallieni
Porte de Bagnolet
Mairie de Montreuil
Franklin D. Roosevelt
Boissière
Alma Marceau
Champs Élysées Clemenceau
Concorde
Pyramides
Palais Royal Musée du Louvre
Louvre Rivoli
Étienne Marcel
Les Halles
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Filles du Calvaire
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Rue Saint-Maur
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Philippe Auguste
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Invalides
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Musée d'Orsay
Pont Neuf
Châtelet
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Hôtel de Ville
Chemin Vert
Richard Lenoir
Voltaire
Alexandre Dumas
Croix de Chavaux
Robespierre
Porte de Montreuil
Maraîchers
Avron
Buzenval
Marne-la-Vallée
La Muette
Passy
La Tour Maubourg
Assemblée Nationale
Solférino
St-Paul
Bréguet Sabin
Charonne
Bastille
Rue des Boulets
Boulainvilliers
Champ de Mars Tour Eiffel
Bir-Hakeim
École Militaire
Varenne
Rue du Bac
Saint Germain des-Prés
St-Michel
St-Michel Notre-Dame
Pont Marie
Sully Morland
Ledru-Rollin
Faidherbe Chaligny
Nation
Vincennes
Ranelagh
Avenue du Pdt Kennedy
Dupleix
La Motte Picquet Grenelle
Saint François Xavier
Sèvres Babylone
Mabillon
Odéon
Cluny La Sorbonne
Maubert Mutualité
Cardinal Lemoine
Quai de la Rapée
Reuilly – Diderot
Porte de Vincennes
St-Mandé
Boissy-St-Léger
Picpus
Vaneau
Saint-Sulpice
Luxembourg
Jasmin
Michel Ange
Église d'Auteuil
Javel
Cambronne
Ségur
Duroc
St-Placide
Notre-Dame
Jussieu
Gare de Lyon
Montgallet
Bel-Air

Driving a Subway Train Is Easy. . . Is It?

- Only two buttons: start and stop.
  - No crossroads, no people crossing, . . .
- Should be easy to automate!
- But...
  - Wait for people to get on board.

[1] Same with trains, only worse.

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  - And, if it doesn't, how long does it take to reproduce the bug in your computer?
  - Or, plainly, how can you reproduce it?

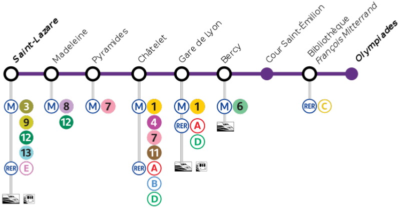
[1] Same with trains, only worse.

Towards an Automatically Managed Subway Line

- Add extra sensors.
- Add extra mechanisms (doors apart apart from coaches').
- Model the enviroment very precisely.
- Correctness by Construction.

Paris Metro Line 14

- October 15th, 1998, Tolbiac to Madeleine.
  (Now extended)
- 40000 passenger / hour, 85 sec. between trains in peak hour.
- 2009: 60 million passengers / year.
- Decision based on previous experience:
  - Completely automated line.
  - Completely developed using formal methods for control systems.
  - Having manually and automatially driven trains.



Subsystems

- Automatic control and signaling.
- Platform doors.
- Audio and Video.
- Operating control center.

Subsystems

- **Automatic control and signaling.**
  - In the train.
  - In the operating control center.
  - Along the tracks.
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- **Automatic control and signaling**.
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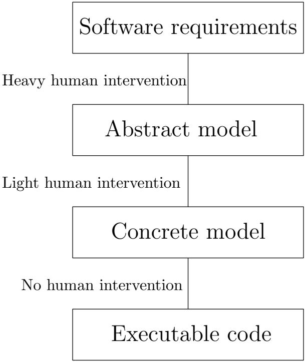
  - Running alone on specific, non-interruptible, microprocessor boards.
- Platform doors.
- Audio and Video.
- Operating control center.
- Developed using the *B Method* [Abr96], now evolved into Event B [Abr10].

Correctness by construction

Make sure that every step is correct

A Taste of B

- **Model** the problem.
- **Determine** the properties to hold.
- **Refine** the model (several times, adding more details).
- **Prove** that the refinement is correct.



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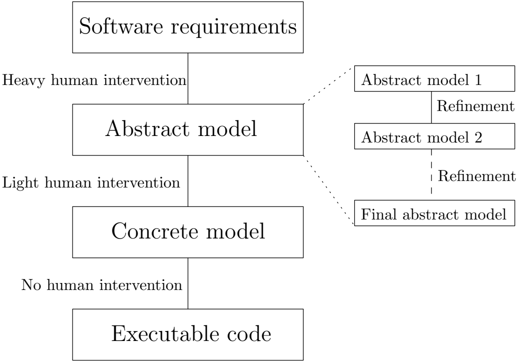

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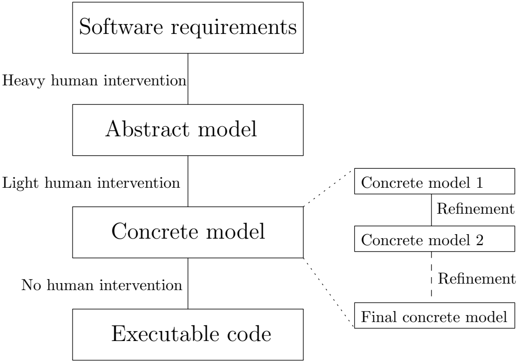

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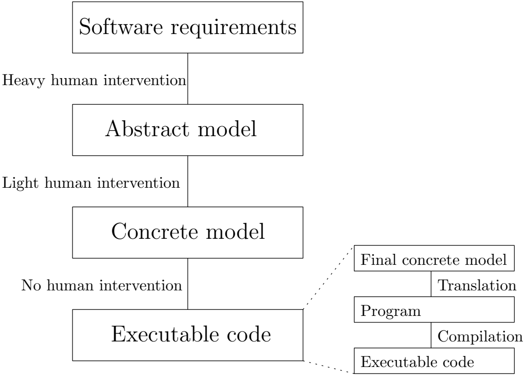

INVARIANTS

invBDay : $birthday \in PERSON \nrightarrow DATE$

EVENTS

Initialisation

begin

initBDay : $birthday := \varnothing$

end

Event *addBDay* $\widehat{=}$

any

p, d

where

inPerson : $p \in PERSON$

inDate : $d \in DATE$

then

newBDay : $birthday(p) := d$

end

END

INVARIANTS

`invBDay` : $birthday \in PERSON \pfun DATE$

EVENTS

Initialisation

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Event *addBDay* $\widehat{=}$

any

p, d

where

`inPerson` : $p \in PERSON$

`inDate` : $d \in DATE$

`checkBday` : $p \notin dom(birthday)$

then

`newBDay` : $birthday(p) := d$

end

END

Proofs: Prove **mathematically** refinements are right.

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$$\dfrac{\dfrac{}{n>0 \vdash 0=0}\ \text{EQL} \qquad \dfrac{}{n>0 \vdash n>0}\ \text{HYP}}{n>0 \vdash (n>0 \wedge 0=0)}\ \text{AND\_R}$$

$$n>0 \vdash (n<d \wedge 0=0) \vee (n>0 \wedge 0=0) \quad \text{OR\_R}$$

$$\dfrac{\dfrac{}{n<d \vdash 0=0}\ \text{EQL} \qquad \dfrac{}{n<d \vdash n<d}\ \text{HYP}}{n<d \vdash (n<d \wedge 0=0)}\ \text{AND\_R}$$

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$$n>0 \vee n<d \vdash (n<d \wedge 0=0) \vee (n>0 \wedge 0=0) \quad \text{OR\_L}$$

$$b=n, n>0 \vee n<d \vdash (b<d \wedge 0=0) \vee (b>0 \wedge 0=0) \quad \text{EQ\_LR}$$

$$0+b+0=n, n>0 \vee n<d \vdash (0+b<d \wedge 0=0) \vee (b>0 \wedge 0=0) \quad \text{ARITH}$$

$$a+b+0=n, n>0 \vee n<d, a=0 \vdash (a+b<d \wedge 0=0) \vee (b>0 \wedge a=0) \quad \text{EQ\_LR}$$

$$a \in \mathbb{N}, a+b+0=n, n>0 \vee n<d, \neg(a>0) \vdash (a+b<d \wedge 0=0) \vee (b>0 \wedge a=0) \quad \text{ARITH}$$

$$a \in \mathbb{N}, a+b+0=n, n>0 \vee n<d \vdash (a+b<d \wedge 0=0) \vee a>0 \vee (b>0 \wedge a=0) \quad \text{NEG}$$

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$$a, b, c, d, n \in \mathbb{N}, 0<d, n \leq d, a+b+c=n, a=0 \vee c=0, 0<n \vee n<d \vdash (a+b<d \wedge c=0) \vee c>0 \vee a>0 \vee (b>0 \wedge a=0) \quad \text{MON}$$

Proofs: Prove **mathematically** refinements are right.

$$\dfrac{\dfrac{\dfrac{}{n > 0 \vdash 0 = 0}\ \text{EQL} \quad \dfrac{}{n > 0 \vdash n > 0}\ \text{HYP}}{n > 0 \vdash (n > 0 \land 0 = 0)}\ \text{AND\_R}}{n > 0 \vdash (n < d \land 0 = 0) \lor (n > 0 \land 0 = 0)}\ \text{OR\_R}$$

$$\dfrac{\dfrac{\dfrac{}{n < d \vdash 0 = 0}\ \text{EQL} \quad \dfrac{}{n < d \vdash n < d}\ \text{HYP}}{n < d \vdash (n < d \land 0 = 0)}\ \text{AND\_R}}{n < d \vdash (n < d \land 0 = 0) \lor (n > 0 \land 0 = 0)}\ \text{OR\_R}$$

OR_L

$$n > 0 \lor n < d \vdash (n < d \land 0 = 0) \lor (n > 0 \land 0 = 0)$$

EQ_LR

$$b = n, n > 0 \lor n < d \vdash (b < d \land 0 = 0) \lor (b > 0 \land 0 = 0)$$

ARITH

Note: invariants are the most important piece of information. Although many proofs are not aimed at establishing invariants, virtuall all of them involve invariants.

TH

$$0 \lor (b > 0 \land a = 0)$$

ARITH

$$a, c \in \mathbb{N}, a + b + c = n, n > 0 \lor n < d, \neg(c > 0) \vdash (a + b < d \land c = 0) \lor a > 0 \lor (b > 0 \land a = 0)$$

NEG

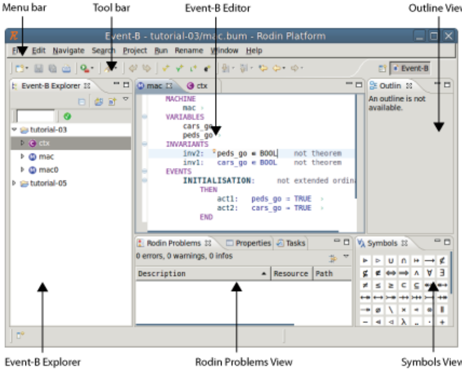
$$a, c \in \mathbb{N}, a + b + c = n, n > 0 \lor n < d \vdash (a + b < d \land c = 0) \lor c > 0 \lor a > 0 \lor (b > 0 \land a = 0)$$

MON

$$a, b, c, d, n \in \mathbb{N}, 0 < d, n \leq d, a + b + c = n, a = 0 \lor c = 0, 0 < n \lor n < d \vdash (a + b < d \land c = 0) \lor c > 0 \lor a > 0 \lor (b > 0 \land a = 0)$$

Tools!

- Automate some (many) proofs.
- Automatically generate code.
- Many advantages when code is generated.
- Example at hand: code duplication.
  - Electronic in tunnels: interference with boards.
  - Possible corruption of data.
  - All data duplicated in different formats.
  - Code works on both copies.
  - Constant comparison for consistency.



Statistics

- **Lines of B:** 115.000 .
- **Lines of Ada:** 86.000 .
- **Lemmas of B:** 27.800 .
- **Automatically proven:** 92%.
- **Time to develop:** 4 years (aprox.)

Statistics

- **Lines of B:** 115.000 .
- **Lines of Ada:** 86.000 .
- **Lemmas of B:** 27.800 .
- **Automatically proven:** 92%.
- **Time to develop:** 4 years (aprox.)

- **Bugs in development computer:** 0
- **Bugs in target computer:** 0
- **Bugs in on-site tests:** 0
- **Bugs since deployment:** 0

Part III

Amazon Had 2.000.000.000.000 Things to Care About [NTZ+14]

Landscape

Some numbers for AWS's S3

- 2013: 2.000.000.000.000 (2 trillions) objects, 1.1 million requests per second.
- High availability.
- Scalability.
- S3 just one AWS service.
- Essential complexity high → unavoidable human errors.

Previously in...

- Standard “verification” techniques in industry.
  - Deep design reviews.
  - Code reviews (c.f. DB train code reviews).
  - Static code analysis.
  - Stress testing.
  - Fault-injection testing.
  - . . .

. . . human intuition is poor at estimating the true probability of supposedly “extremely rare” combinations of events in systems operating at a scale of millions of requests per second.

The History According to the Starring Roles

- Engineer C.N. dissatisfied with bugs in implementaions of distributed algorithms.
- Looked for ways to correct them — not thinking on formal methods.
- But read paper on formal verification of Chord using Alloy.
- Tried to use it, but not rich enough — no good for formal methods!

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- But read paper on formal verification of Chord using Alloy.
- Tried to use it, but not rich enough — no good for formal methods!
- C.N. read a paper on Leslie Lamport Paxos algorithm — essential in distributed systems.
- At the end of the paper, a TLA+ [Lam02] / TLC formalization.
- TLA+ also devised by Leslie Lamport.
- Maybe TLA+ / TLC was worth something?
- Tried the same example as in Alloy — success!

The Busy Engineers

- But engineers too busy to try new things.
- Unless there is a new need — and a new need appeared.

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Enter DynamoDB

- Scalable, high-performance, high-availability storage.
- Testing, stressing, fault injection — but really high confidence was necessary.
  - Otherwise data from companies could be lost.
- T.R. (DynamoDB's coauthor) went on to prove relevant properties.
- Informal proofs already found bugs.
- Which other subtle problems could be hidden?

TLA+ Time

- T.R. learned TLA+, formalized (some) DynamoDB algorithms.
- Run distributed version of model checker TLC.
  - Cluster of ten EC^2 instances.
  - Each 8 cores + hyperthreads.
  - 23 GB ram.
- Small part of algorithm OK.
- But in the full fault-tolerance algorithm a bug was found.
  - Very subtle — many conditions had to be met.
  - But historically possible.
  - Bug had passed all reviews.
  - Other two bugs were found later on.

The History Goes On

- New DynamoDB features first modeled and verified in TLA+ — and bugs were found ahead of time.
- Presentation to teams: *Debugging Designs*.
  - *Exahustively testable pseudo-code.*
- New fault-tolerant distributed algorithm specified and checked.
  - Two bugs found.
- Management started pushing TLA+ usage in teams.

What the Protagonists Say...

[...] help engineers to get the design right. [...] If the design is broken then the code is almost certainly broken. Coding mistakes extremely unlikely to compensate mistakes in design.

Engineers probably deceived into believing that code is ‘correct’ because appears to correctly implement the broken design. Unlikely to realize that design is incorrect while focusing on coding.

[...] gain a better understanding of the design. [...] can only increase chances that they will get code right.

[...] write better assertions [...], a good way to reduce errors in code.

Formal methods help engineers to find strong invariants, so formal methods can help to improve assertions, which help improve the quality of code.

Part IV

That Is Not What I Meant [PPS+03]

A Different Problem

How misleading are (well-written) natural language specifications?

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- In general, a lot.
- Natural language is ambiguous.
- Even if it's not, it relies a lot on “common knowledge” or “situational knowledge”.
- Kids give us lots of examples: flawless reasoning without knowledge.

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- We buy another faucet.
- (Pointing below the sink). Look: the tap gets water from the pipe, which comes from the wall. Buying another faucet will not help. Now, what would be do?

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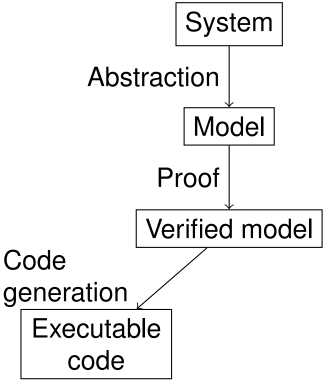
- We buy another wall.

A Different Experiment

- Existing, well-proven implementation of a smartcard.
- Natural language specification.
- How well can a team of engineers capture understand these specifications?

Using Models to Generate Tests



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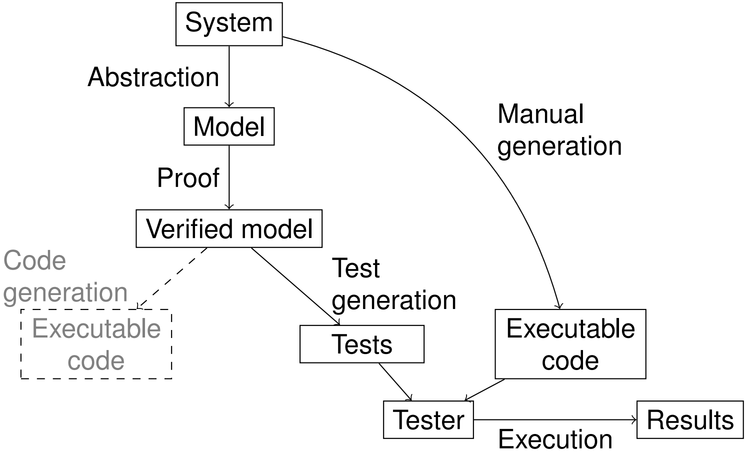

A SmartCard is...

- Fully programmable one-chip computer.
- Microprocessor, RAM (currently 256-4096 Bytes), EEPROM (2-16 KBytes), and ROM (8-64 KBytes).
- Hierarchical filesystem.
- Serial interface.
- Sometimes specialized cryptographic microprocessor.

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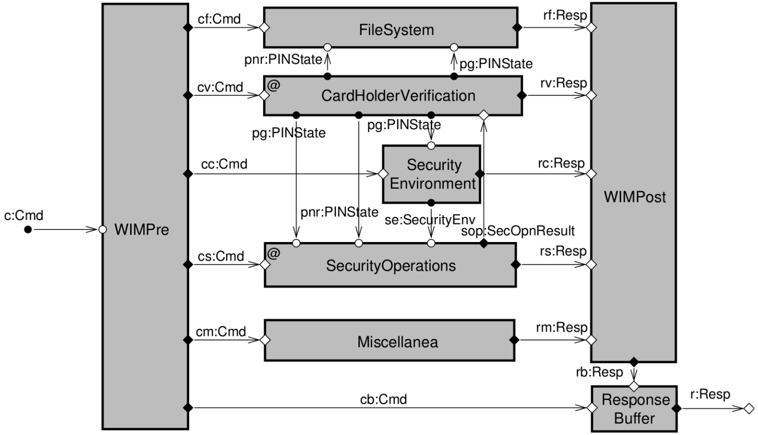
- Hierarchical filesystem.
- Serial interface.
- Sometimes specialized cryptographic microprocessor.
- Command interpreter:
  - Read commands from stdin.
  - Interpret, execute, write output to stdout.
  - Execution usually depends on previous commands.

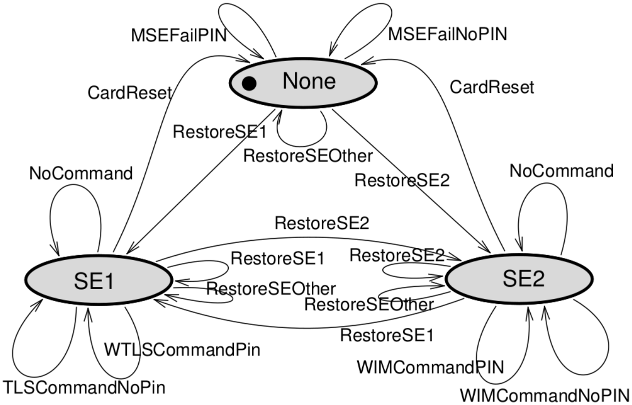
System Under Study

- WAP module in GSM standard, implemented in a SmartCard.



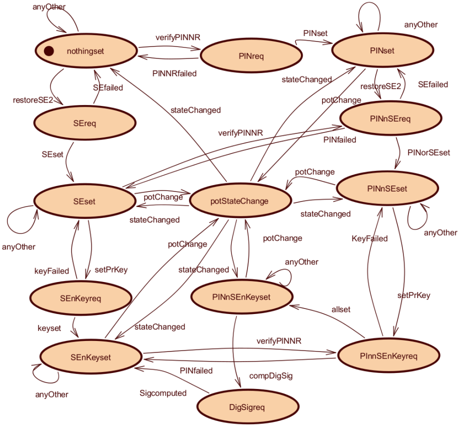
Subcomponents

- Each subcomponent has a expected behavior (i.e., what it expects to receive and return in every state).

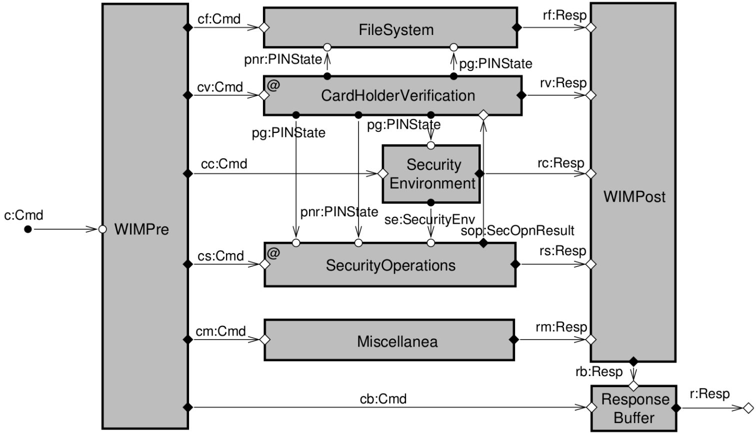


Tester: Behavior

From the behavior of the component one can extract the expected behavior of the tester: what it has to do at every moment to check the component.



The System to Test



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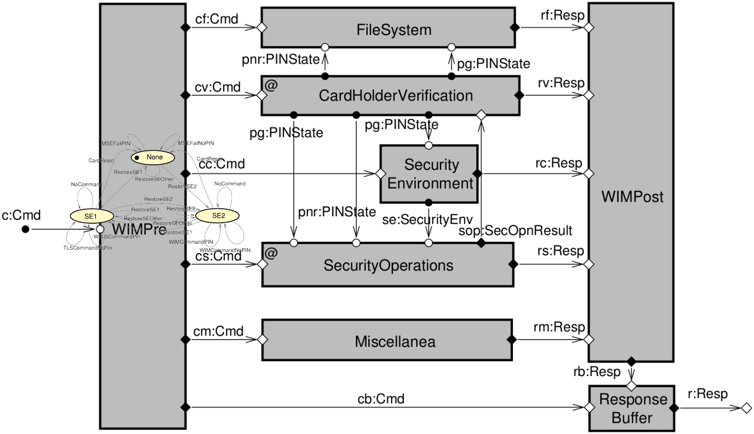

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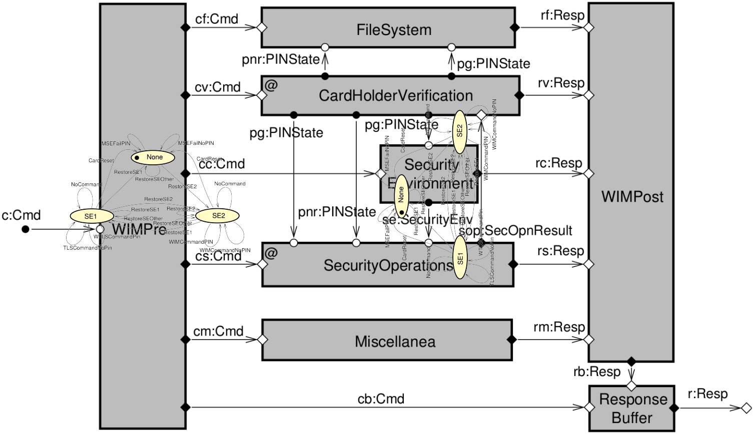

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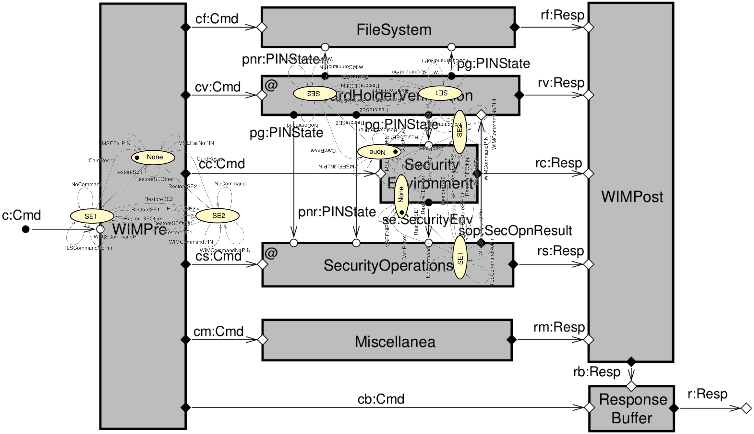

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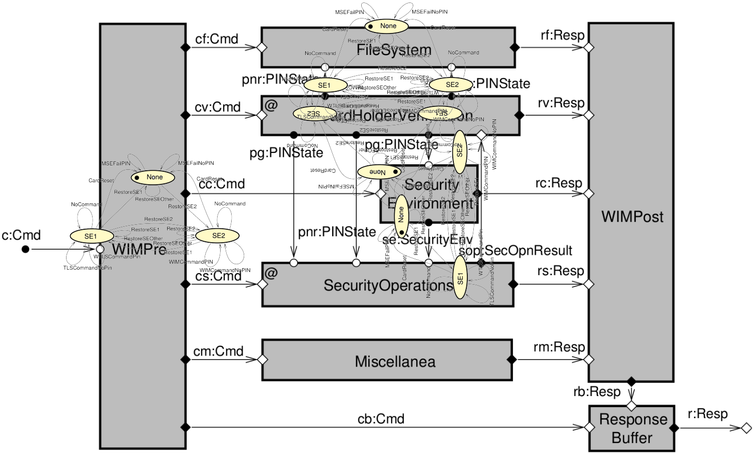

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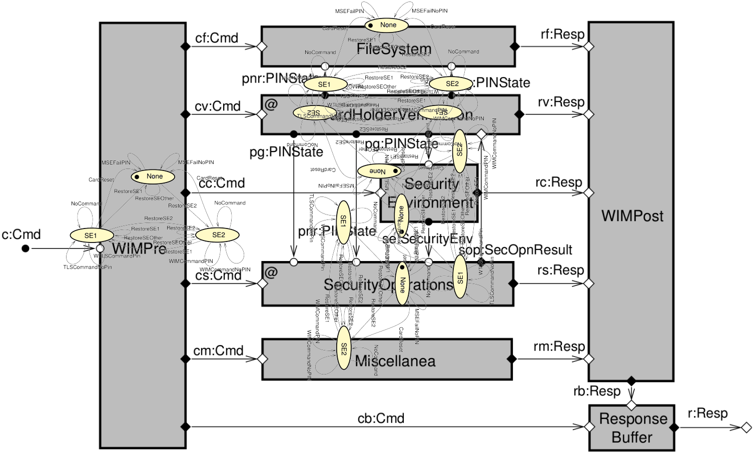

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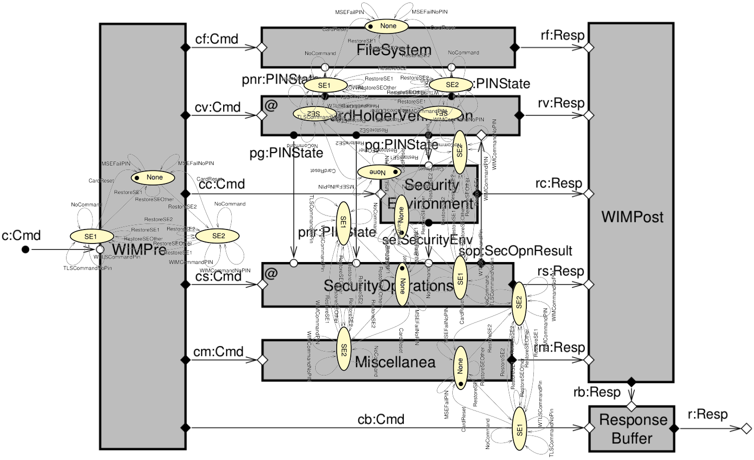

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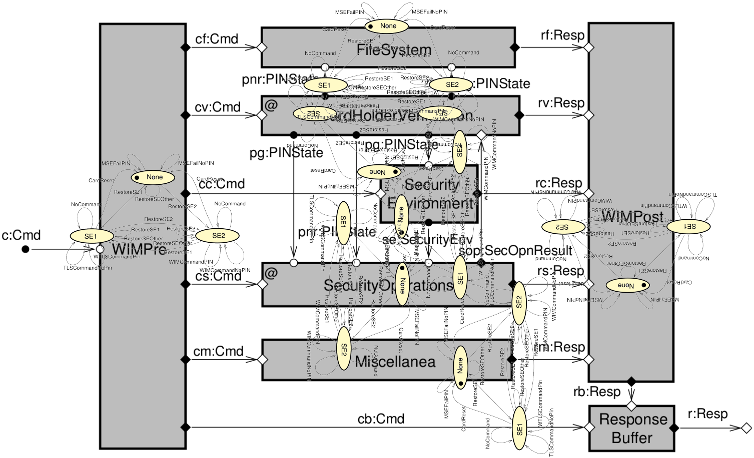

The Behavior of the Test Suite

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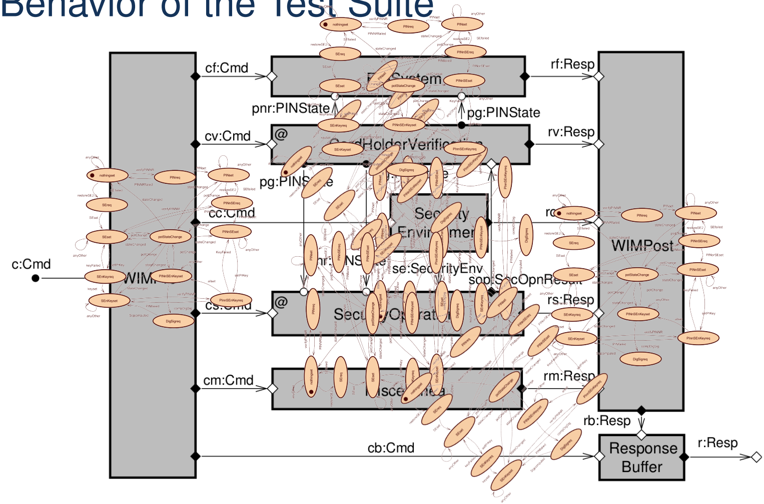

Test Coverage and Generation

- Testing cannot (in general) ensure correctness.
- Only existence of errors can be proven.
- Exhaustive testing: very expensive
  (in time to generate tests and to execute them)
- Test generation needs to execute the program.
  - *If I call operation A with data D, which output would I obtain?*

Test Generation for the SmartCard

- Using CLP.
- For a component **a** with a state machine, a collection of clauses like

```
step_a(StateIn, Input, StateOut, Output):-
    guard(StateIn, Input),
    assign(StateIn, Input, StateOut, Output).
```

- Different components can be chained togeter:

```
step_comp(StateIn, In, StateOut, Out):-
    step_a(StateOut, In, S0, O0),
    step_b(S0, O0, S1, O1),
    ...
    step_k(Sn, On, StateOut, Out).
```

- Enumerate traces.
- Use constraints to reduce trace sizes.

CLP to Reduce Traces

- Transition has to read value v from input channel i.

```
v = read(i);
if (v == k) then ...
else ...
```

- In **`else`** branch: assuming all possible values for **`v`** not feasible.
- Make a trace with $v = k$ and another with $v \neq k$.
- Constraint in the latter $\rightarrow$ generate refined feasible traces later on.
  - Requiring $v = k$ after that $\rightarrow v \neq k \wedge v = k \rightarrow$ trace not generated.
  - A trace that requires $v \geq k$ is reduced to requiring $v > k$.
- Using sets of values (= constraints) helps reduce the search space.
- Still, some operations are difficult to model.
- **`AskRandom(n)`**: only length modeled.

Evaluation

- 60.000 test sequences, varying length.
- Testing with only 2%-3% of sequences.
- Around one hour to execute.
- Summary: out of 1506 test sequences, 84 mistmatches.
- All of them due to misinterpretation of documentation or faults in recently optimized versions of software.

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1. Make no assumptions.
2. Premature optimization is the root of all evil.

Part V

What Now?

Conclusions

- Yes, formal methods are used in industry — more than usually thought.
- **Not** to write payroll software.
  - But payroll software is already written...
- High-availability, dependable software.
  - NASA; Prolog to formalize JVM class system; SLAM at Microsoft; Esterel for hardware, avionics, and cars; Airbus; . . .
    automotive industry, cyber-physical systems.
- Also to discover bugs in existing implementations.
  - E.g., FREAK SSL negotiation bug — team INRIA, Microsoft Research, IMDEA Software Institute.

Recommendations [BH06] and Old Man Sayings

- Use well-tested, well-documented formal method.
- With tool support.
- If possible, have an expert at hand – at least at the beginning.
- Document everything: every assumption, every decision.
- Don't lower quality standards.
- Test and test again.

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- If possible, have an expert at hand – at least at the beginning.
- Document everything: every assumption, every decision.
- Don't lower quality standards.
- Test and test again.
- Trying to formalize will force you to think about a problem. Thinking about a problem will make you understand it.

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Formal Methods at Work

M. Carro

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Technical University of Madrid

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