Experiments on automation of formal verification of devices at the binary level

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Soutenance de PFE (Option R&D)

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Section 1

Motivation

Table of Contents

Security critical systems

Privacy

- Smartphones
- Smart TVs

Integrity

- Hospital equipment
- Traffic control systems
- Power plants

Security critical systems

Integrity

- Hospital equipment
- Traffic control systems
- Power plants

Privacy

- Smartphones
- Smart TVs

Problem: complex systems almost always contain bugs

Security critical systems - vulnerable

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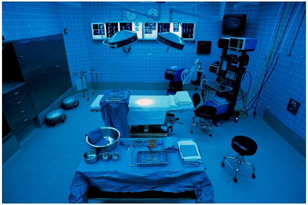

Figure: "It's Insanely Easy to Hack Hospital Equipment" [4]

Security critical systems - vulnerable

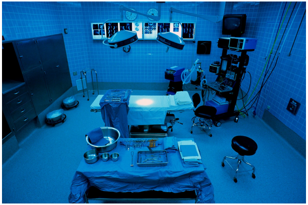

Figure: "It's Insanely Easy to Hack Hospital Equipment" [4]

- Remote control of equipment

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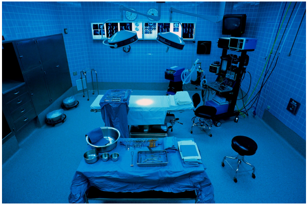

Figure: "It's Insanely Easy to Hack Hospital Equipment" [4]

Figure: "Remote Exploitation of an Unaltered Passenger Vehicle" [1, 2]

- Remote control of equipment

Security critical systems - vulnerable

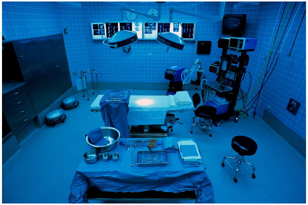

Figure: "It's Insanely Easy to Hack Hospital Equipment" [4]

- Remote control of equipment

Figure: "Remote Exploitation of an Unaltered Passenger Vehicle" [1, 2]

- Total control of drive systems

Secure operating systems

Security. Performance. Proof.

[1] https://sel4.systems/Info/FAQ/proof.pml

Secure operating systems

Formal proof[1]:

- The binary code correctly implements its **abstract specification**.
- The specification guarantees **integrity** and **confidentiality**.

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Secure operating systems

Formal proof[1]:

- The binary code correctly implements its **abstract specification**.
- The specification guarantees **integrity** and **confidentiality**.

- **Integrity**: data cannot be *changed* without permission.
- **Confidentiality**: data cannot be *read* without permission.

[1] `https://sel4.systems/Info/FAQ/proof.pml`

Secure operating systems

Proof assumptions[2]:

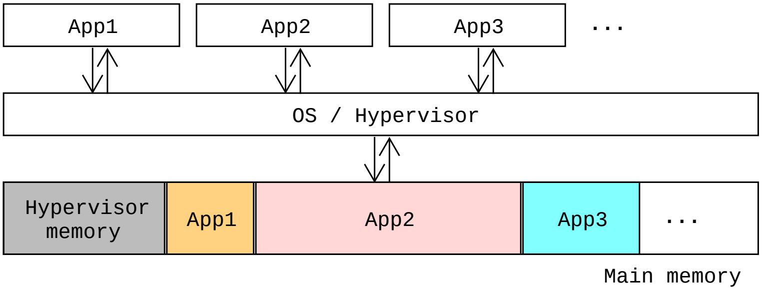
[2] https://docs.sel4.systems/FrequentlyAskedQuestions#is-sel4-proven-secure

Secure operating systems

Proof assumptions[2]:

- Use of Direct Memory Access (DMA) is excluded, or only allowed for **trusted drivers that have to be formally verified by the user**.

[2] https://docs.sel4.systems/FrequentlyAskedQuestions#is-sel4-proven-secure


App1
App2
App3
...
OS / Hypervisor
Hypervisor memory
App1
App2
App3
...
Main memory

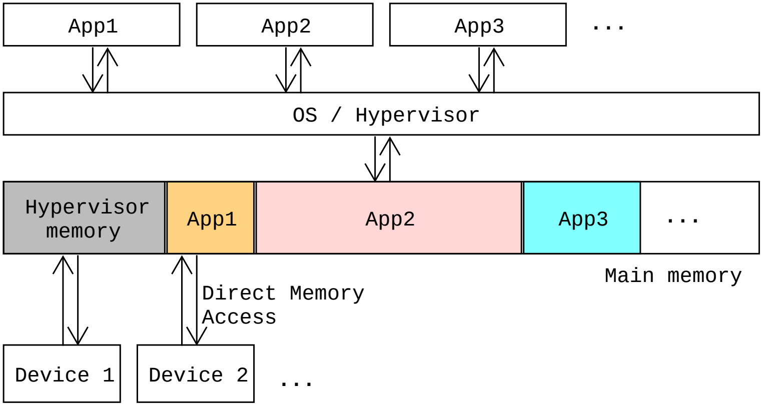

App1
App2
App3
...
OS / Hypervisor
Hypervisor memory
App1
App2
App3
...
Main memory
Direct Memory Access
Device 1
Device 2
...

Table of Contents

System software verification

Objective: show absence of errors in modelisation of real systems

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Formal proof

machine checkable proofs using
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specialized programs or procedures that check a given property

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$\rightarrow$ produced theorems are trustworthy

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Classic bug-prone software
$\rightarrow$ need tests, less trustworthy

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Examples: HOL4, Coq, Isabelle

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Formal proof	**Non proof-producing verification**
machine checkable proofs using rigorous semantic	specialized programs or procedures that check a given property
Use small reliable kernels $\rightarrow$ produced theorems are trustworthy	Classic bug-prone software $\rightarrow$ need tests, less trustworthy
Examples: HOL4, Coq, Isabelle	SMT solvers, model checkers

Table of Contents

Network Interface Controller (NIC)

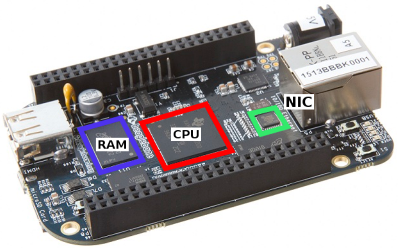
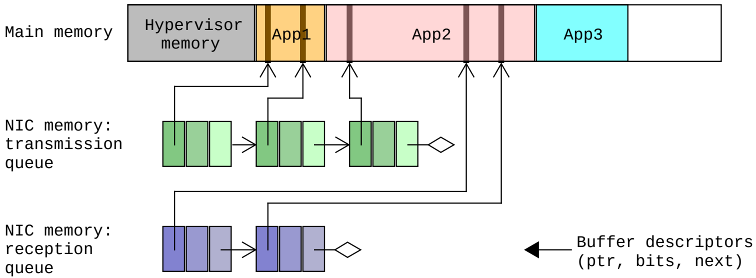


Figure: BeagleBone Black.

NIC: How it works



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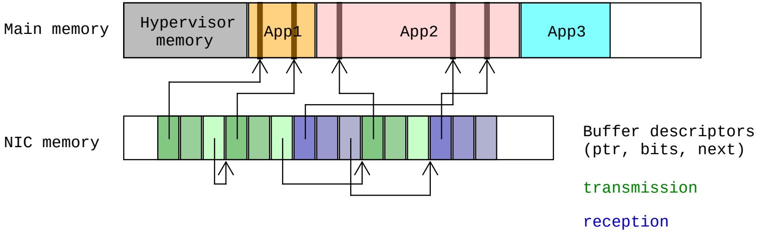
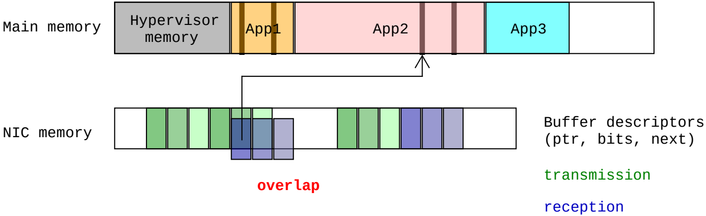


NIC: How it can fail



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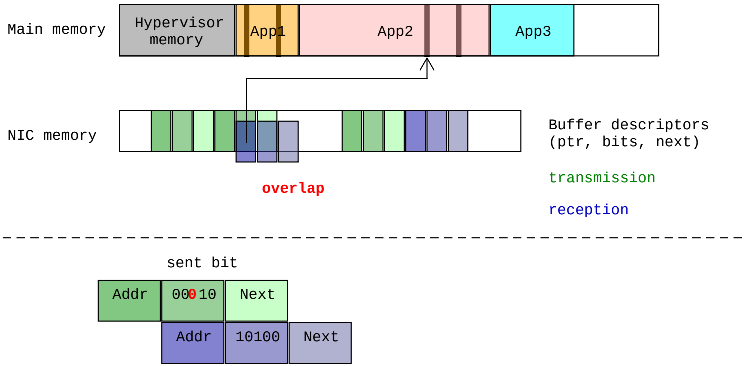

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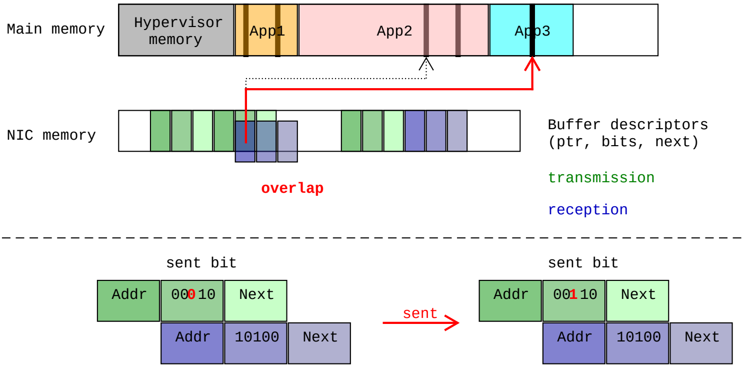
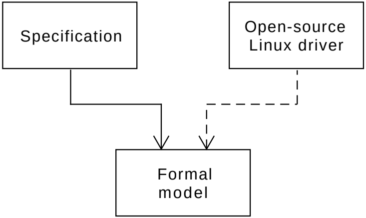


NIC: How it has been modeled



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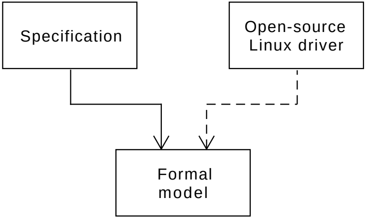
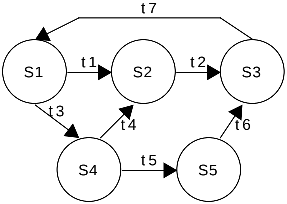


Transition system:



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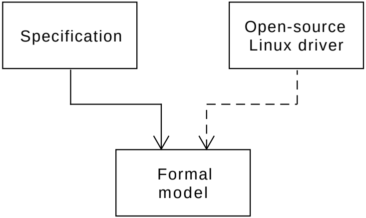

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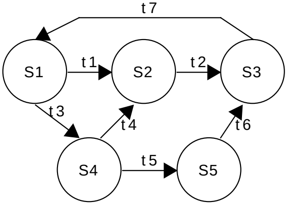
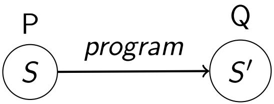


Unspecified behavior → "dead" state

Hoare Triple

Hoare Triple



Hoare Triple

$$\forall S.\ P(S)$$

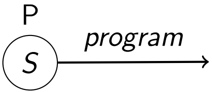
P

S

$\{P\}$

Hoare Triple

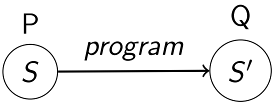
$$\forall S.\ P(S)\ \wedge\ S' = program(S)$$



$$\{P\}\ program$$

Hoare Triple

$$\forall S.\ P(S)\ \wedge\ S' = program(S) \implies Q(S')$$



$$\{P\}\ program\ \{Q\}$$

Weakest precondition

Weakest precondition WP such that:

$$\{WP\}\ program\ \{Q\}$$

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Weakest precondition WP such that:

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$$WP = f(program,\ Q)$$

NIC: What the verification looks like

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Low-level lemmas:

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- $\{\neg dead \wedge well\_configured\}\ transition\ \{\neg dead\}$

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Intermediate lemmas:

- *Invariant*: $rx\_invariant\_well\_defined$
- *Invariant*: $tx\_invariant\_well\_defined$

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- $Invariant$: $rx\_invariant\_well\_defined$
- $Invariant$: $tx\_invariant\_well\_defined$

Security theorems:

- $\forall\ tx\_bd.\ readable(tx\_bd)$ $BD = Buffer\ Descriptor$
- $\forall\ rx\_bd.\ writable(rx\_bd)$

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Security theorems:

- $\forall\ tx\_bd.\ readable(tx\_bd)$ *BD = Buffer Descriptor*
- $\forall\ rx\_bd.\ writable(rx\_bd)$

Research question

Can we apply traditional software verification techniques and tools to show security properties of hardware devices?

HolBA: HOL4 Binary Analysis platform

- Verification platform at binary level
- Centered around its Intermediate Language, BIR
- Features proof-producing tools
  - Weakest precondition generation

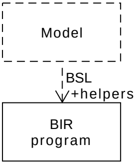
Section 2

Contract-based verification

Table of Contents

Contract-based verification pipeline

0. Translate the model in BIR

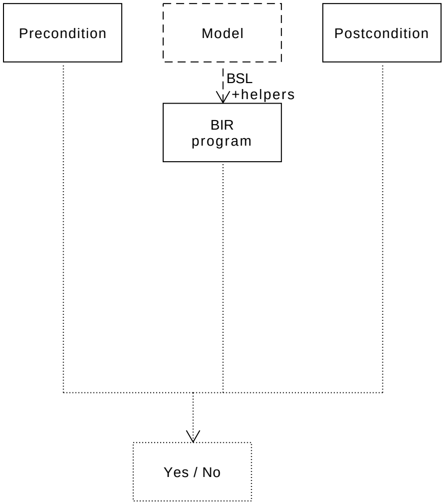


$transition_{BIR}$

Contract-based verification pipeline

0. Translate the model in BIR
1. Formulate a Hoare Triple

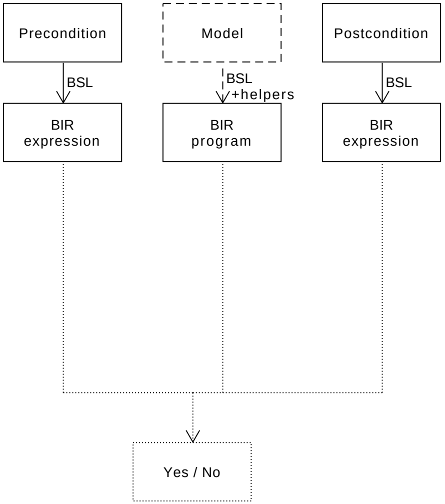
$$\{P\}\ transition_{BIR}\ \{Q\}$$



Contract-based verification pipeline

0. Translate the model in BIR
1. Formulate a Hoare Triple
2. Translate P and Q to BIR

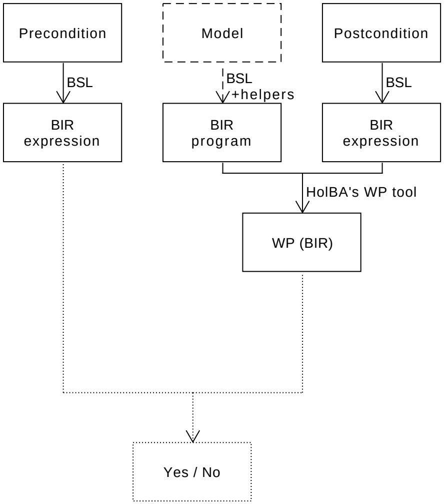
$$\{P_{BIR}\}\ transition_{BIR}\ \{Q_{BIR}\}$$



Contract-based verification pipeline

0. Translate the model in BIR
1. Formulate a Hoare Triple
2. Translate P and Q to BIR
3. Generate the WP

$$P_{BIR}(S) \implies WP_{BIR}(S)$$



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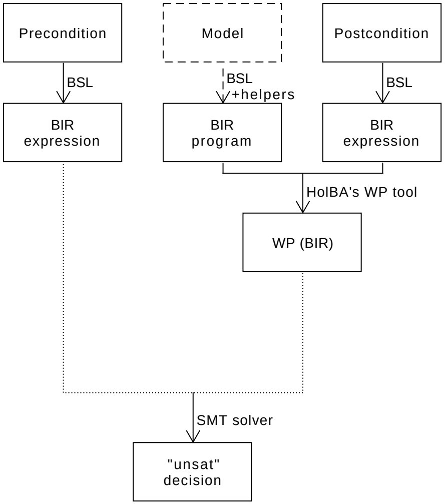


Satisfiability Modulo Theories

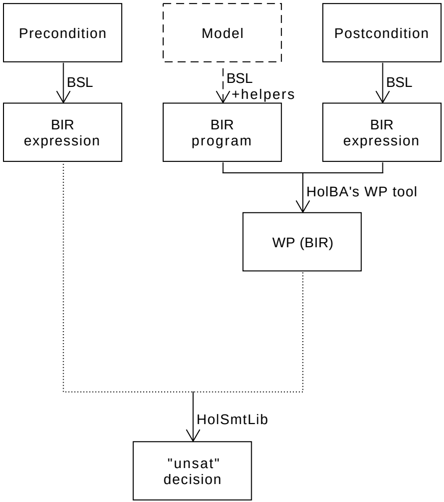
- external tools
- SMT-LIB 2.0

Contract-based verification pipeline

0. Translate the model in BIR
1. Formulate a Hoare Triple
2. Translate P and Q to BIR
3. Generate the WP

$$\neg\left(P_{BIR}(S) \implies WP_{BIR}(S)\right)$$

"unsat"?



Contract-based verification pipeline

0. Translate the model in BIR
1. Formulate a Hoare Triple
2. Translate P and Q to BIR
3. Generate the WP
4. Translate the goal into a SMT-compatible expression

$$\neg\Big(P(S) \implies WP(S)\Big)_{SMT}$$

"unsat"?

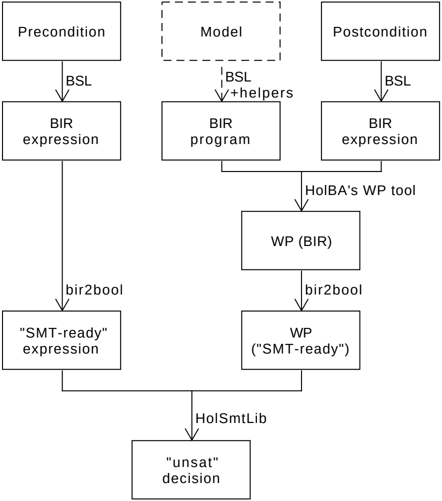
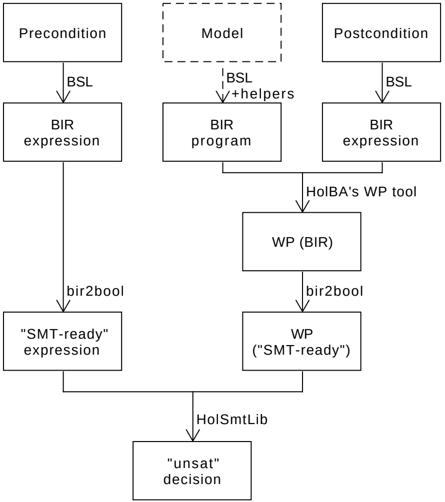


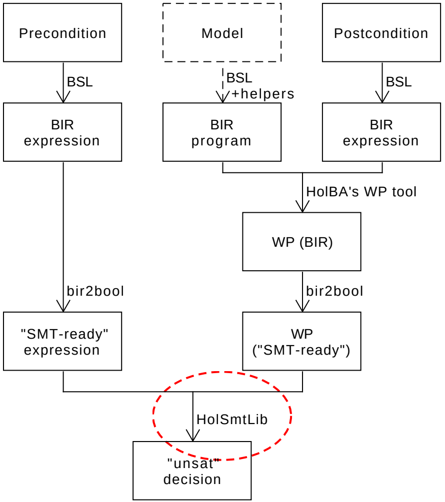
Table of Contents

How trustful is it?



How trustful is it?

- SMT solver don't produce proofs



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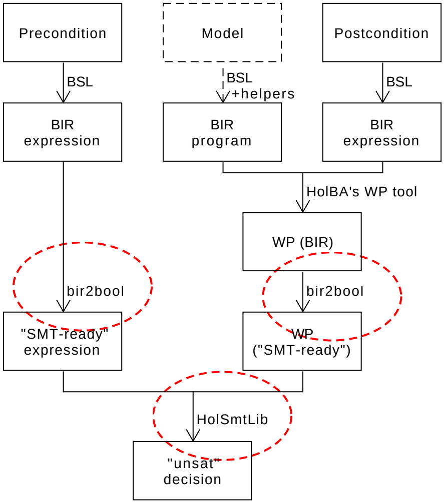
- bir2bool isn't proof-producing



How trustful is it?

- SMT solver don't produce proofs
- bir2bool isn't proof-producing
- The BIR model may be wrong

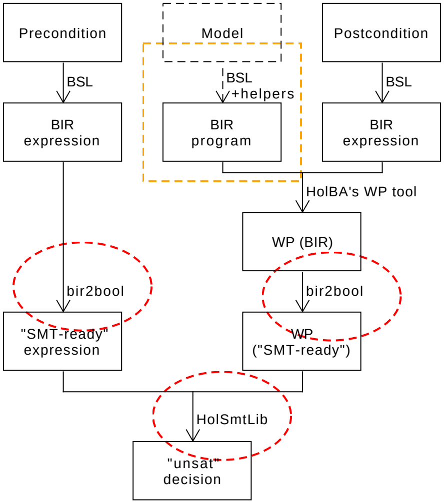


Table of Contents

How powerful is it?

Not proof-producing

Easier non-proof producing platforms exist

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Cannot compose theorems

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- Logic: **QF**_AUFBV $\rightarrow$ **Q**uantifier-**F**ree

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Cannot compose theorems

- HolBA limitation
- Need theorems to compose trustfully

Section 3

Proof-producing verification

Table of Contents

Title

Section 4

Conclusion

Questions

References I

Andy Greenberg.
Hackers remotely kill a jeep on the highway—with me in it.

Dr Charlie Miller and Chris Valasek.
Remote exploitation of an unaltered passenger vehicle.
page 91.

Thomas Tuerk.
Interactive theorem proving (ITP) course.

Kim Zetter.
It's insanely easy to hack hospital equipment.

Other tools for software verification

TODO: Jonas' MT, page 46 Section 2.5.4