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

Thomas Lacroix

INSA Lyon
Soutenance de PFE (Option R&D)

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Section 1

Motivation

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Security critical systems

Privacy

- Smartphones
- Smart TVs

Integrity

- Hospital equipment
- Traffic control systems
- Power plants

Security critical systems

Privacy

- Smartphones
- Smart TVs

Integrity

- Hospital equipment
- Traffic control systems
- Power plants

Problem: complex systems almost always contain bugs

Security critical systems - vulnerable

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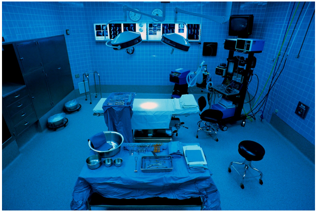

Figure: "It's Insanely Easy to Hack Hospital Equipment" [4]

Security critical systems - vulnerable

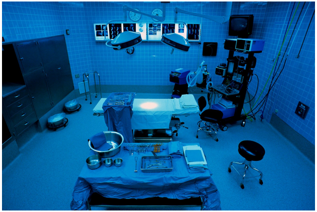

Figure: "It's Insanely Easy to Hack Hospital Equipment" [4]

- Remote control of equipment

Security critical systems - vulnerable

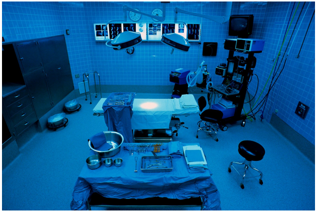

Figure: "It's Insanely Easy to Hack Hospital Equipment" [4]

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

- Remote control of equipment

Security critical systems - vulnerable

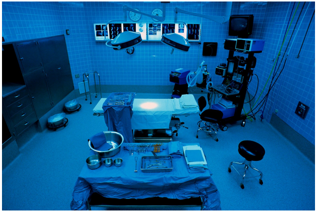

Figure: "It's Insanely Easy to Hack Hospital Equipment" [4]

- Remote control of equipment

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

- Total control of drive systems

Secure operating systems

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

Formal proof[1]:

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

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- 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]:

Security. Performance. Proof.

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

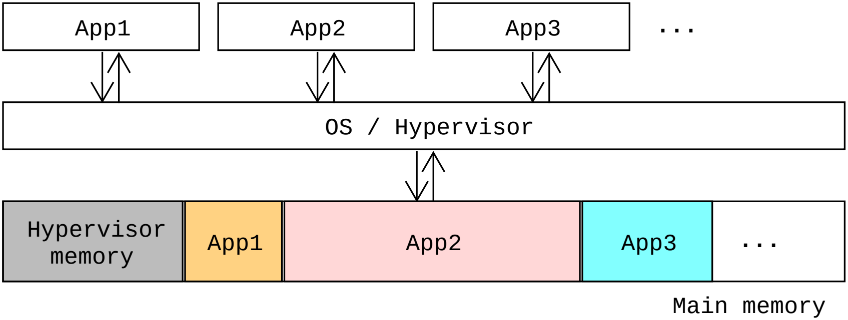
Secure operating systems

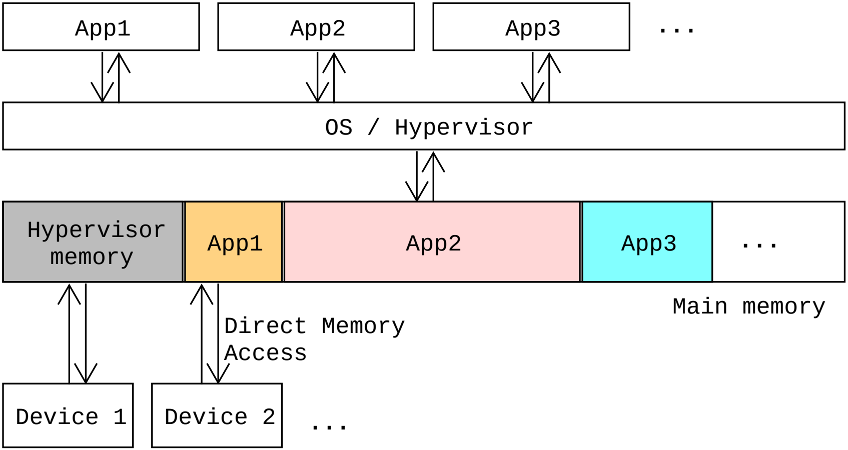
Security. Performance. Proof.

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
...

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System software verification

Objective: show absence of errors in modelisation of real systems

TODO: Ideallement -> implémentation de systems concrets

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machine checkable proofs using

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specialized programs or procedures that check a given property

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Classic bug-prone software
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SMT solvers, model checkers

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Network Interface Controller (NIC)

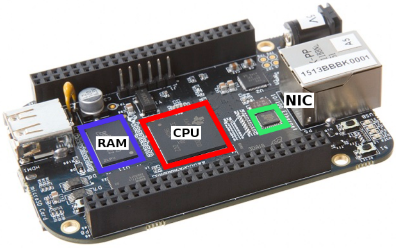
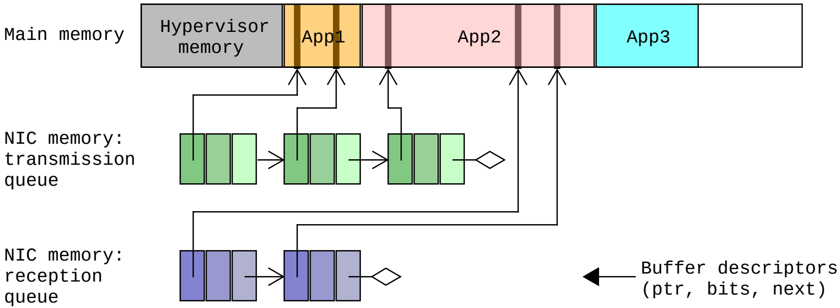


Figure: BeagleBone Black.

NIC: How it works



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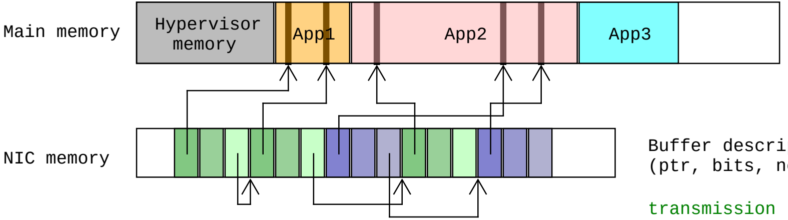
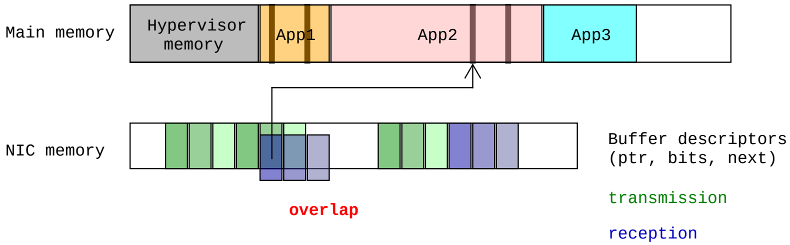


Buffer descriptors
(ptr, bits, next)

transmission

reception

NIC: How it can fail



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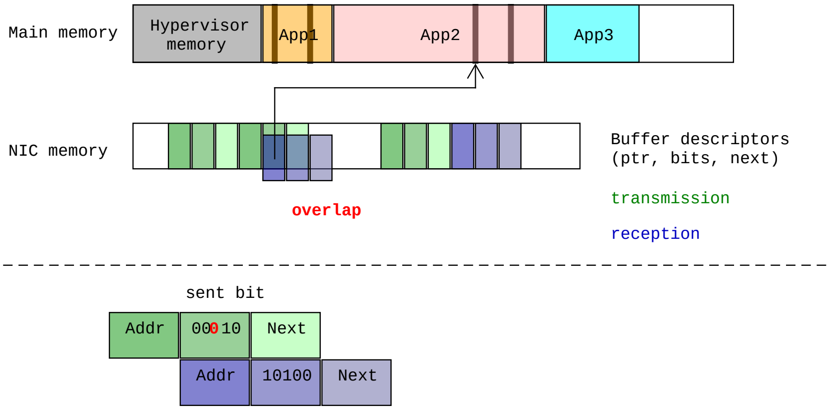

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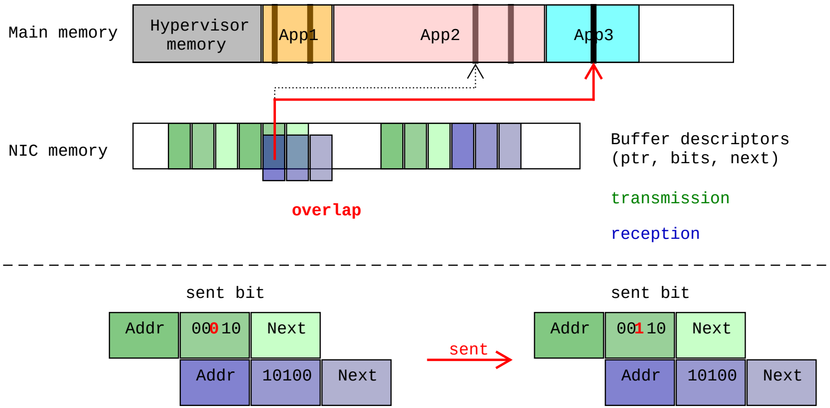
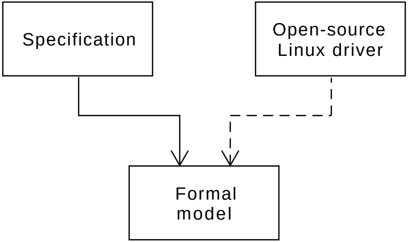


NIC: How it has been modeled



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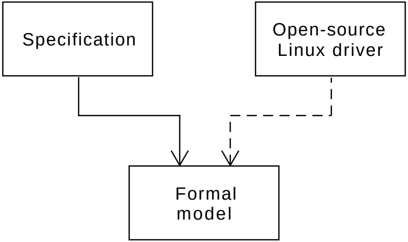
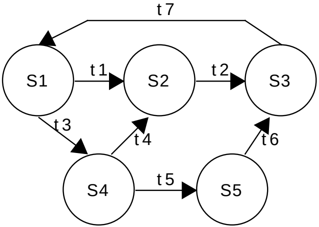


Transition system:



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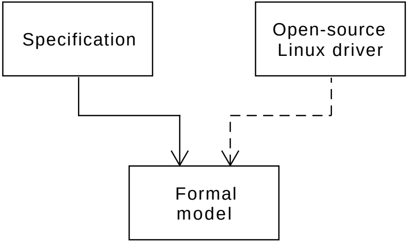

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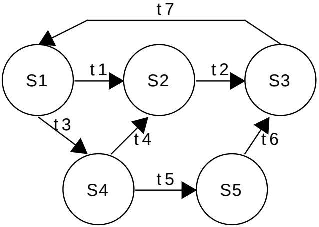
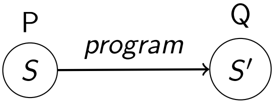


Unspecified behavior → "dead" state

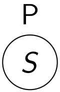
Hoare Triple

Hoare Triple



Hoare Triple

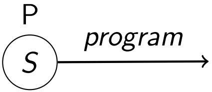
$$\forall S.\ P(S)$$



$$\{P\}$$

Hoare Triple

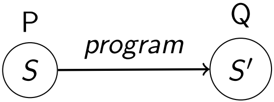
$$\forall S.\ P(S)\ \wedge\ S' = program(S)$$



$$\{P\}\ program$$

Hoare Triple

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



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

Weakest precondition

Weakest precondition *WP* such that:

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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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Intermediate lemmas:

- $Invariant$: $rx\_invariant\_well\_defined$
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- $Invariant$: $rx\_invariant\_well\_defined$
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Security theorems:

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

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Security theorems:

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

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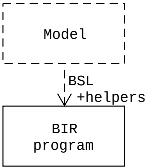
Contract-based verification pipeline

0. Translate the model in BIR

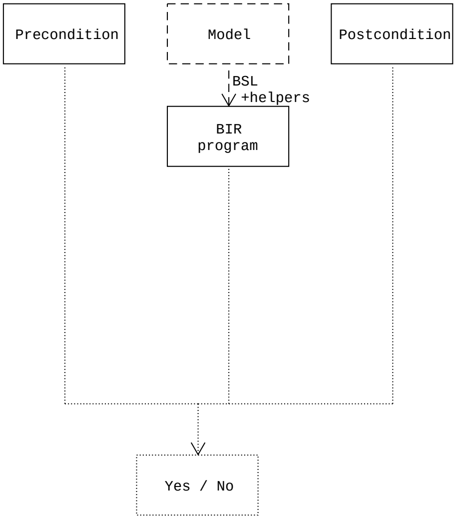


$transition_{BIR}$ **TODO: unique SMT-ready de l'implication**

Contract-based verification pipeline

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

$\{P\}$ $transition_{BIR}$ $\{Q\}$ **TODO: unique SMT-ready de l'implication**

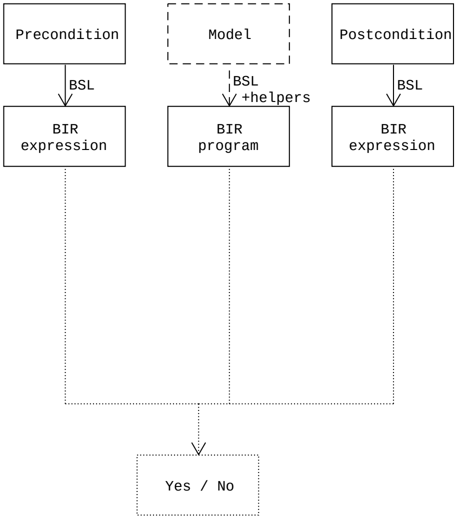


Contract-based verification pipeline

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

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

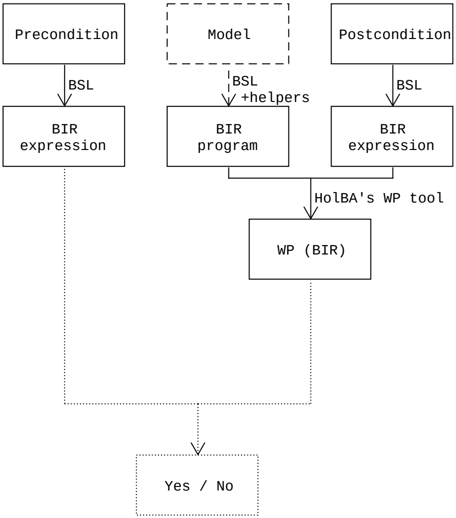
TODO: unique SMT-ready de l'implication



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

$P_{BIR}(S) \implies WP_{BIR}(S)$ **TODO: unique SMT-ready de l'implication**



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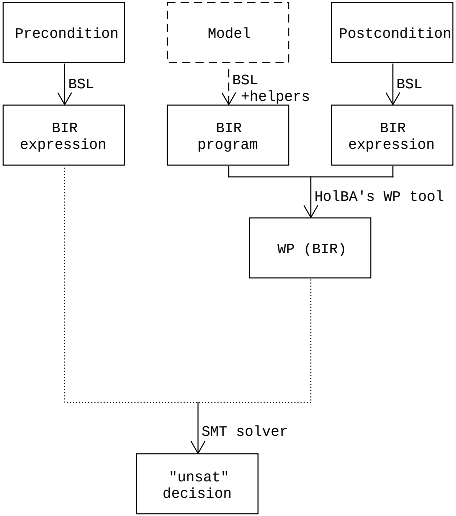

Satisfiability Modulo Theories

- external tools
- SMT-LIB 2.0

TODO: unique SMT-ready de l'implication

Contract-based verification pipeline

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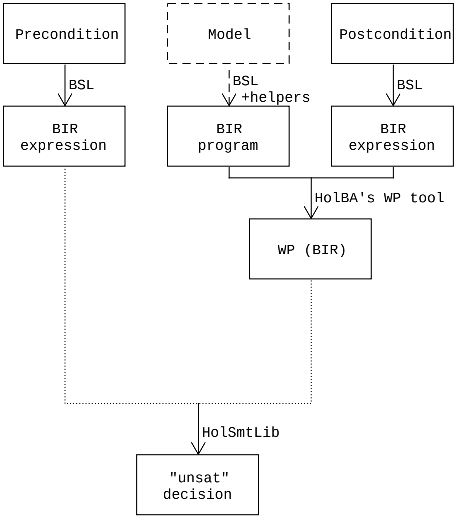
3. Generate the WP



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

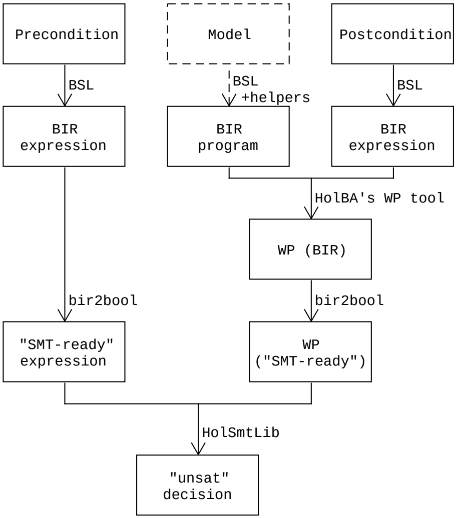
"unsat"? **TODO: unique SMT-ready de l'implication**

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"? **TODO: unique SMT-ready de l'implication**



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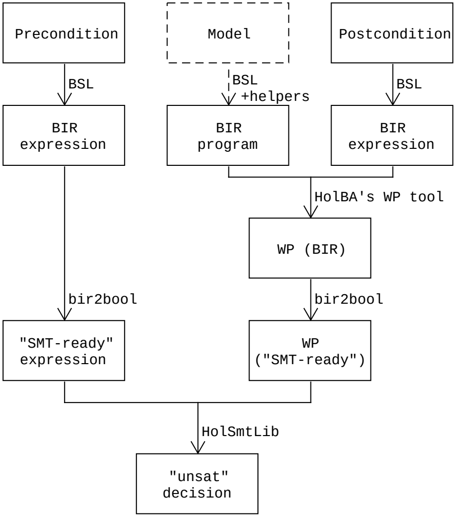
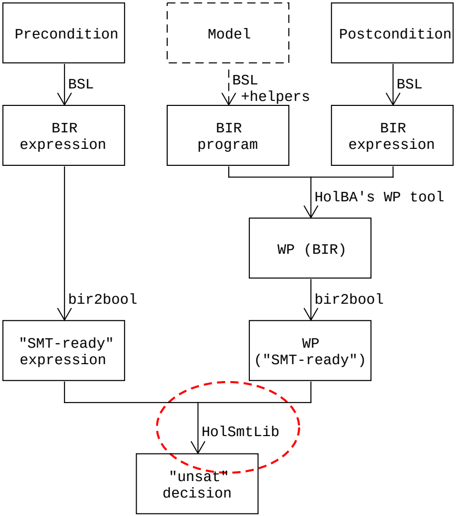
How trustful is it?



How trustful is it?

- SMT solvers don't produce proofs



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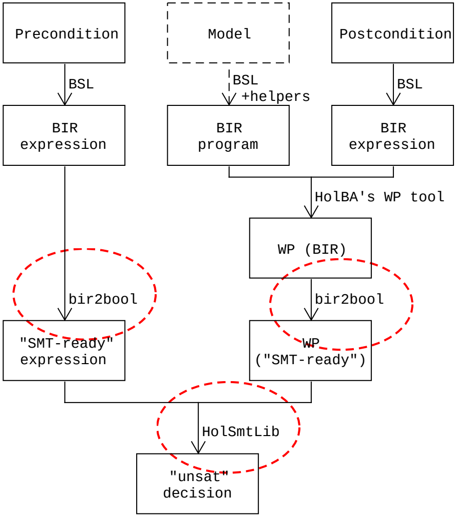
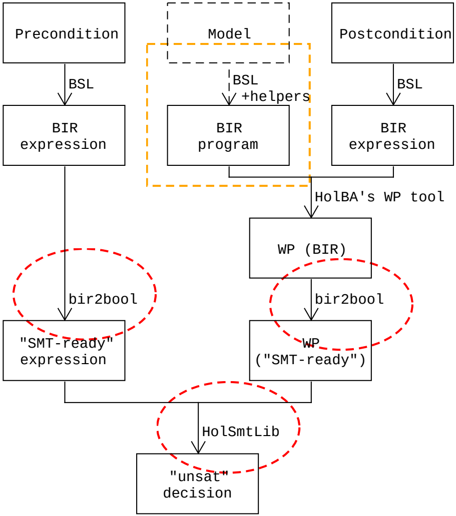


How trustful is it?

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



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How powerful is it?

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Easier non-proof producing platforms exist

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Cannot compose theorems

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Cannot compose theorems

- Partly a limitation of HolBA (work in progress)

Section 3

Proof-producing verification

Goal

Some theorems cannot be proved with previous pipeline
We would like to prove them anyway

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