UNIVERSITY OF WATERLOO

CS 856: Programmable Networks

Lecture 7: Network Verification

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Winter 2024

Logistics

- Project progress report is due **Sunday, March 10th**
  - Two pages
  - Briefly describe the motivation and problem statement
  - Briefly describe the related work, including any new ones you have found since the proposal
  - Describe what you have achieved so far
  - Describe what you plan to do for the rest of the term
- Assignment 2 will be released next week and is optional (extra credit)

Formal Verification

Proving or disproving

the correctness of a (software or hardware) system

with respect to a certain formal specification or property

using formal methods of mathematics

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e.g., Traffic light controller

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Safety properties:
nothing bad happens

e.g., traffic light should not be simultaneously green in both direction

Formal Verification

e.g., Traffic light controller

Proving or disproving

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usi... al methods of ma... atics

Safety properties:
nothing bad happens

e.g., traffic light should not be simultaneously green in both direction

Liveness properties:
something good eventually happens

e.g., If there is a car on the road, the light will eventually turn green

Formal Verification

Broadly applicable!

- Hardware design
- Software
- Distributed systems
- **Computer Networks**
- Aviation
- Neural Networks
- …

Proving o

the correctness of a (sof

with respect to a certain formal specification or property

using formal methods of mathematics

How do we go about verifying a system?

Actual system

Actual Requirements

How do we go about verifying a system?

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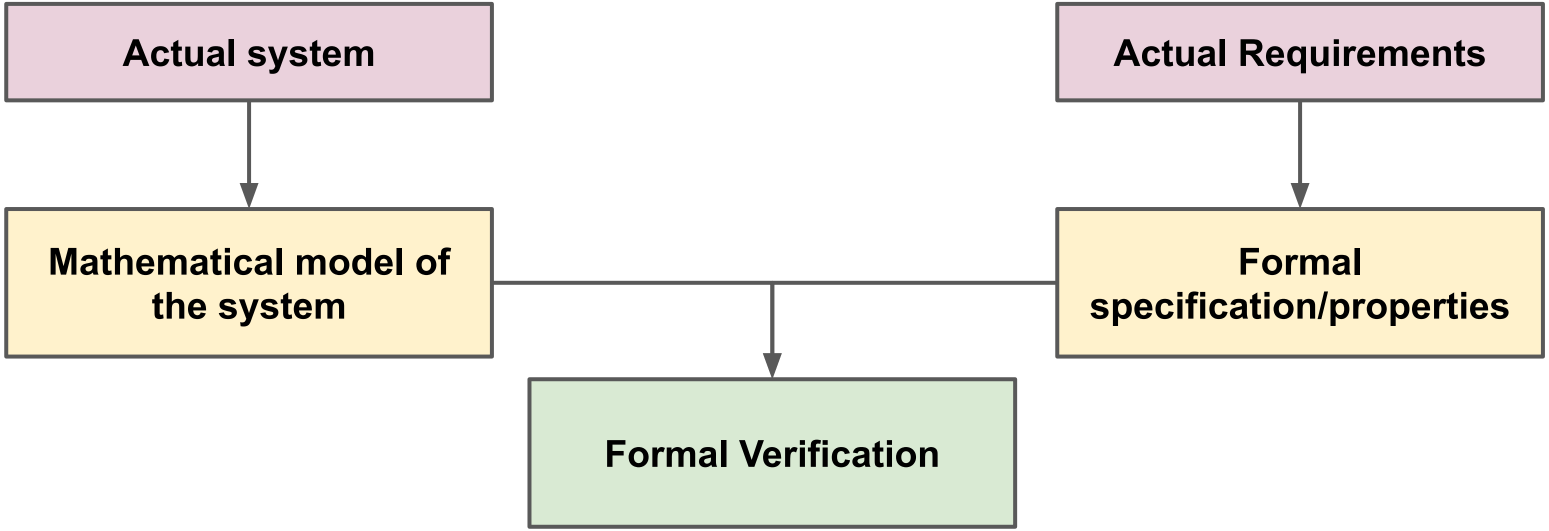

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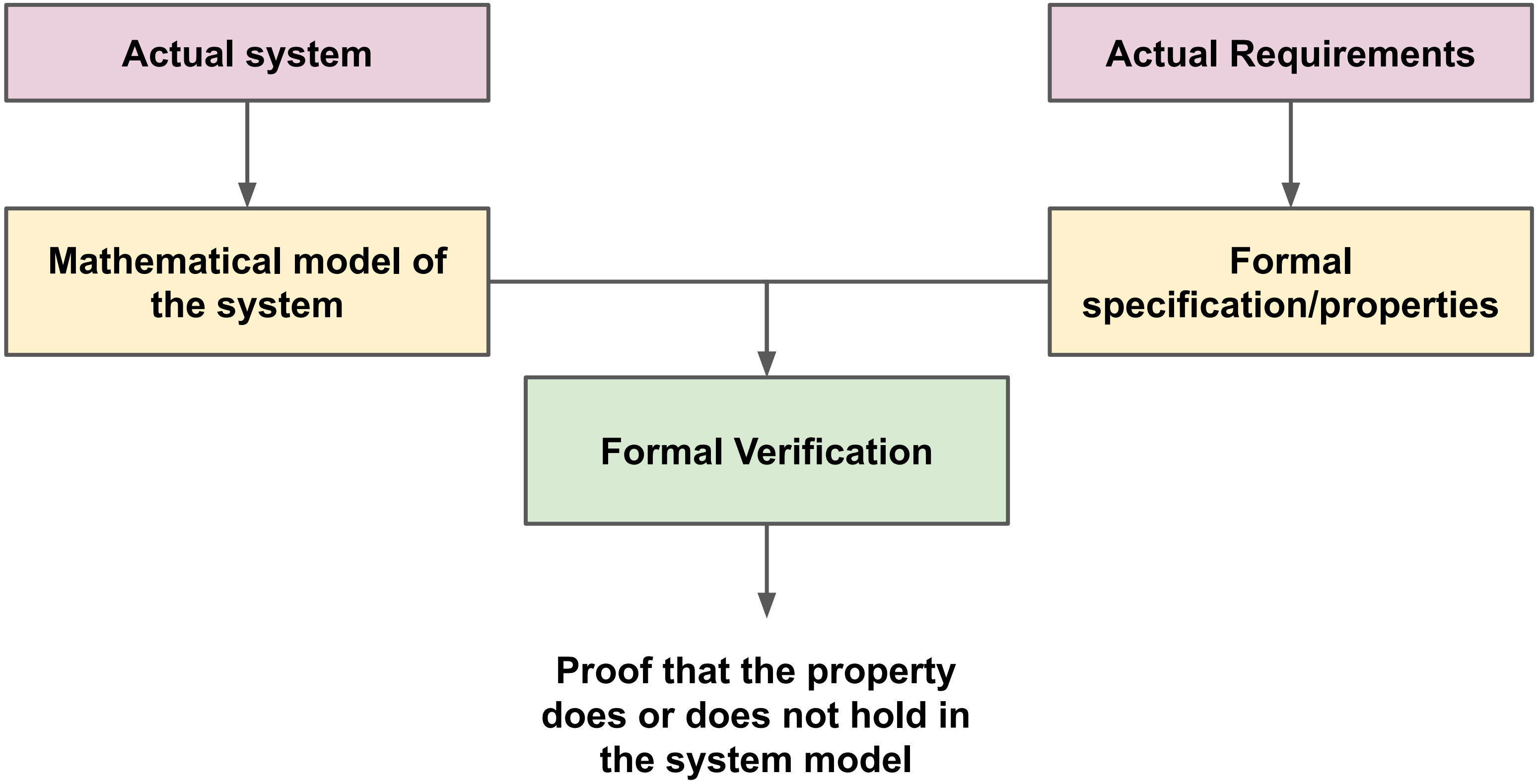

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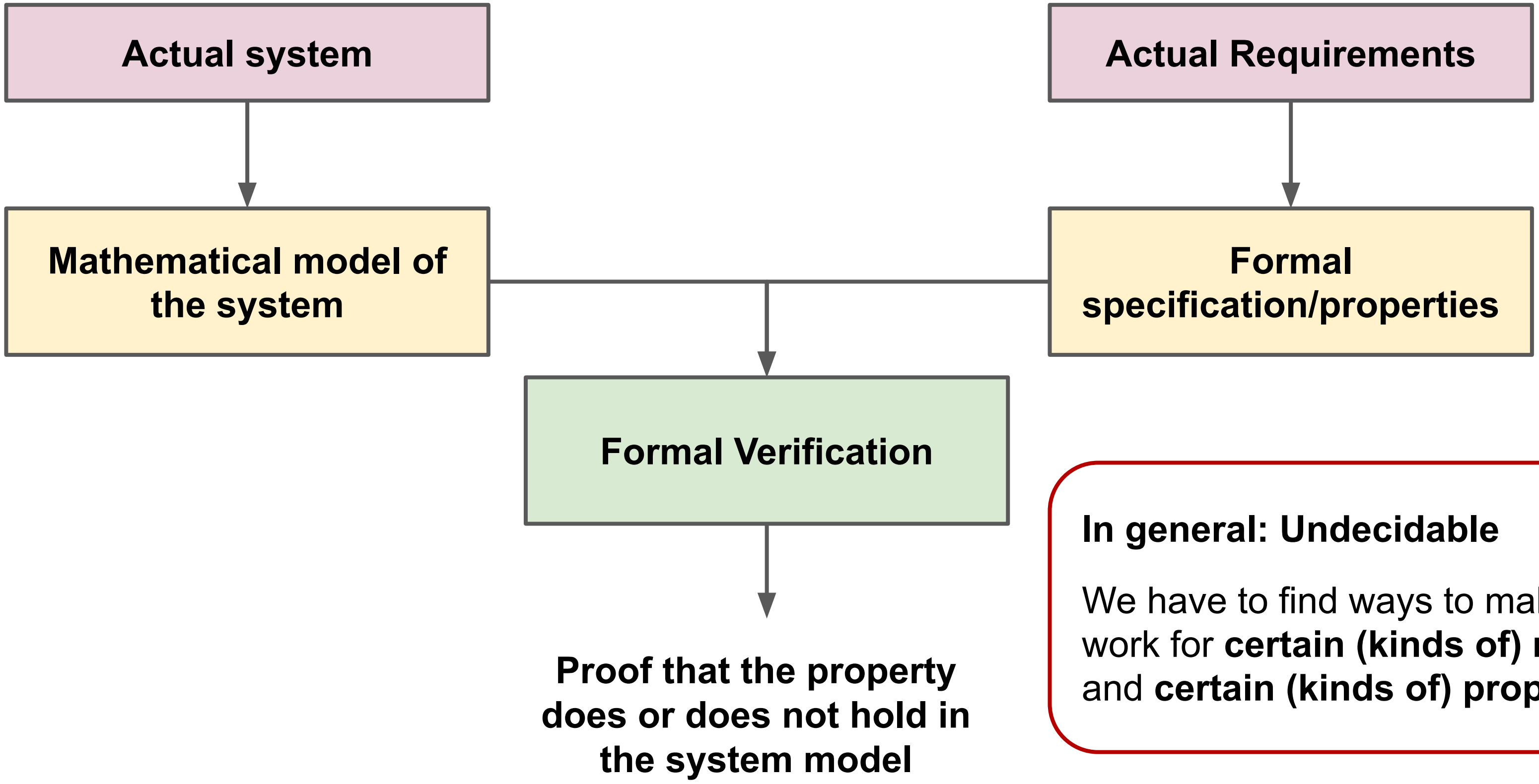

In general: Undecidable

We have to find ways to make it work for **certain (kinds of) models** and **certain (kinds of) properties**

A (very) simple example

The following example is adapted from Aarti Gupta's Fall'15 course on "Automated Reasoning about Software" at Princeton University

A (very) simple example

```
bool x;
int y = 8;
int z = 0;
int w = 0;
if (x)
   z = y - 1
else
   w = y + 1

assert(z == 5
|| w == 9)
```

A (very) simple example

Actual program

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bool x;
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Actual requirements

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Actual requirements

Mathematical model (in logic) of the program

$$(y = 8) \wedge$$

$$(x \rightarrow (z = y - 1)) \wedge$$
$$(\neg x \rightarrow (z = 0)) \wedge$$

$$(x \rightarrow (w = 0)) \wedge$$
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bool x;
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Formal property

$$(z = 5) \,||\, (w = 9)$$

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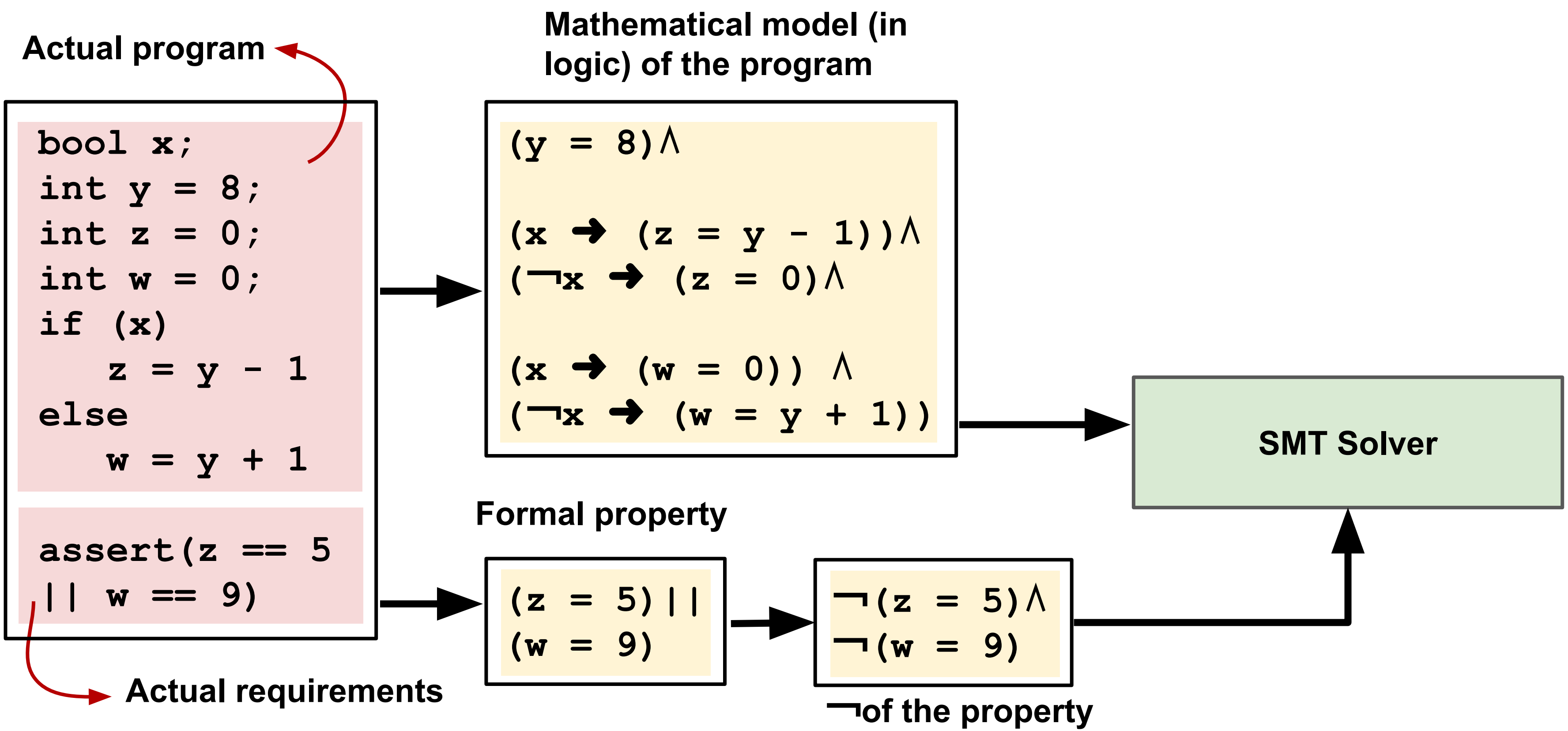
Formal property

$(z = 5) \, || \, (w = 9)$

$\neg(z = 5) \wedge \neg(w = 9)$

$\neg$ of the property

A (very) simple example



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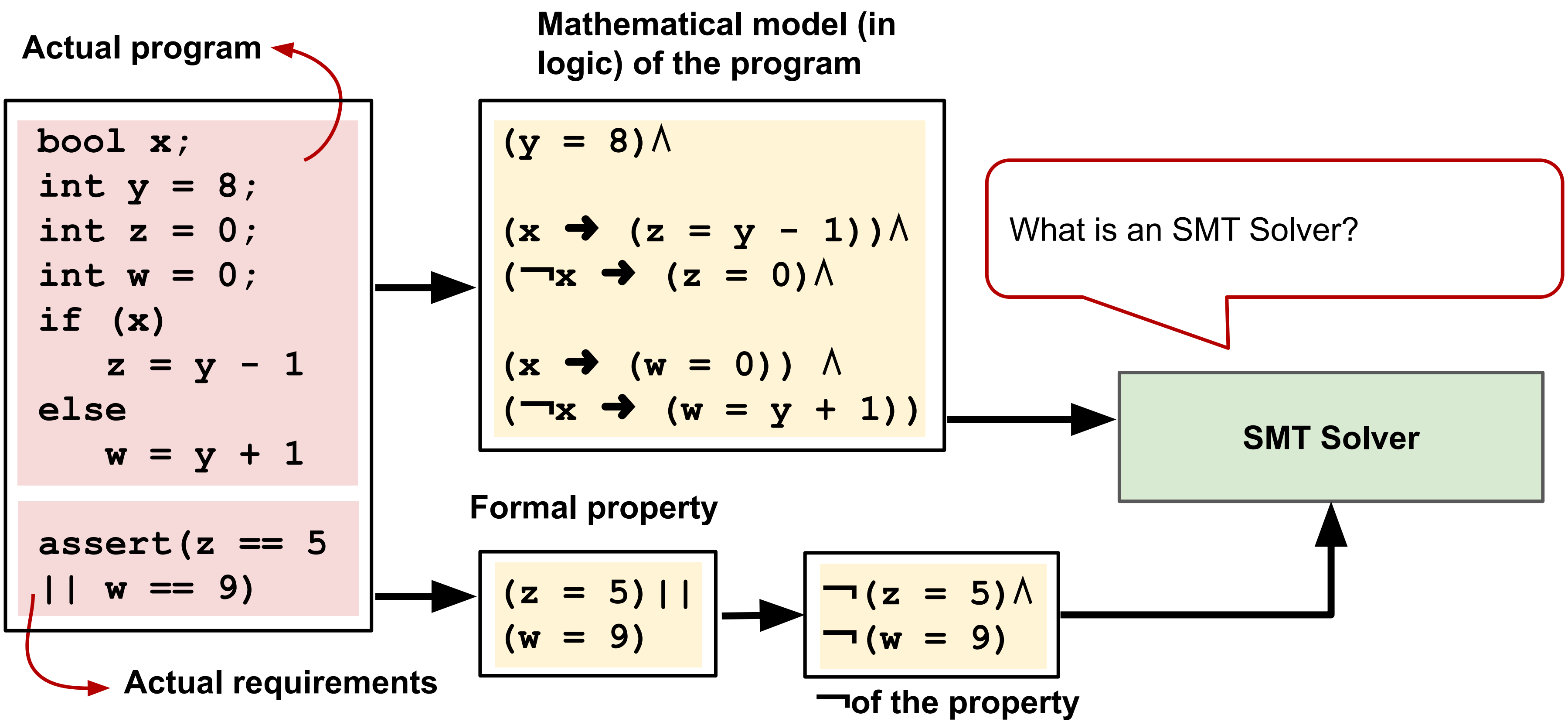


Satisfiability Modulo Theories (SMT)

- Let's look at the boolean satisfiability problem (SAT) first.

The (Boolean) Satisfiability Problem (SAT)

- Suppose you have a boolean formula
    - e.g., $(a \lor b) \land (\neg b \lor c)$
- You can assign true or false to each variable
- Is there an assignment that will make the entire formula evaluate to true?
- This is the SAT problem
- In general, it is NP complete
    - Unless P = NP, it can't be solved in polynomial time

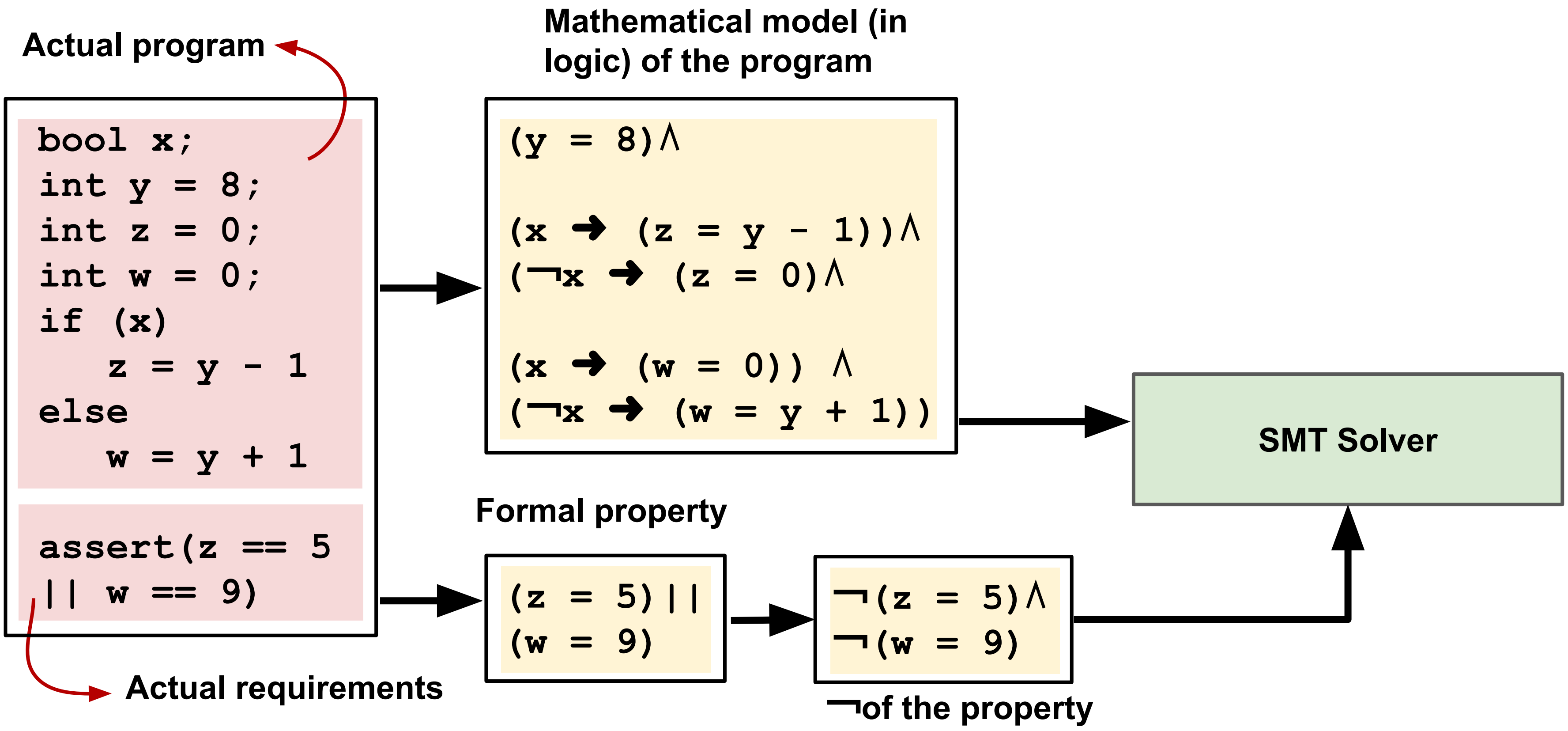
The (Boolean) Satisfiability Problem (SAT)

- The SAT problem, in general, is NP complete
  - Unless P = NP, it can't be solved in polynomial time
- Still, in the formal methods community, there has been a significant progress in tools that can, in many cases, solve this problem quite quickly for large formulas.

Satisfiability Modulo Theories (SMT)

- The same satisfiability problem, but for more complex (first-order-logic) formulas
  - integer variables, real variables, …
  - arrays, bit vectors, lists, strings, …
  - functions such as equality, addition, subtraction, …
- Harder problem
  - can be NP-hard or undecidable depending on the "theory"
- but we have found ways to make it work by finding algorithms for analyzing certain families of formulas ("theories").

A (very) simple example



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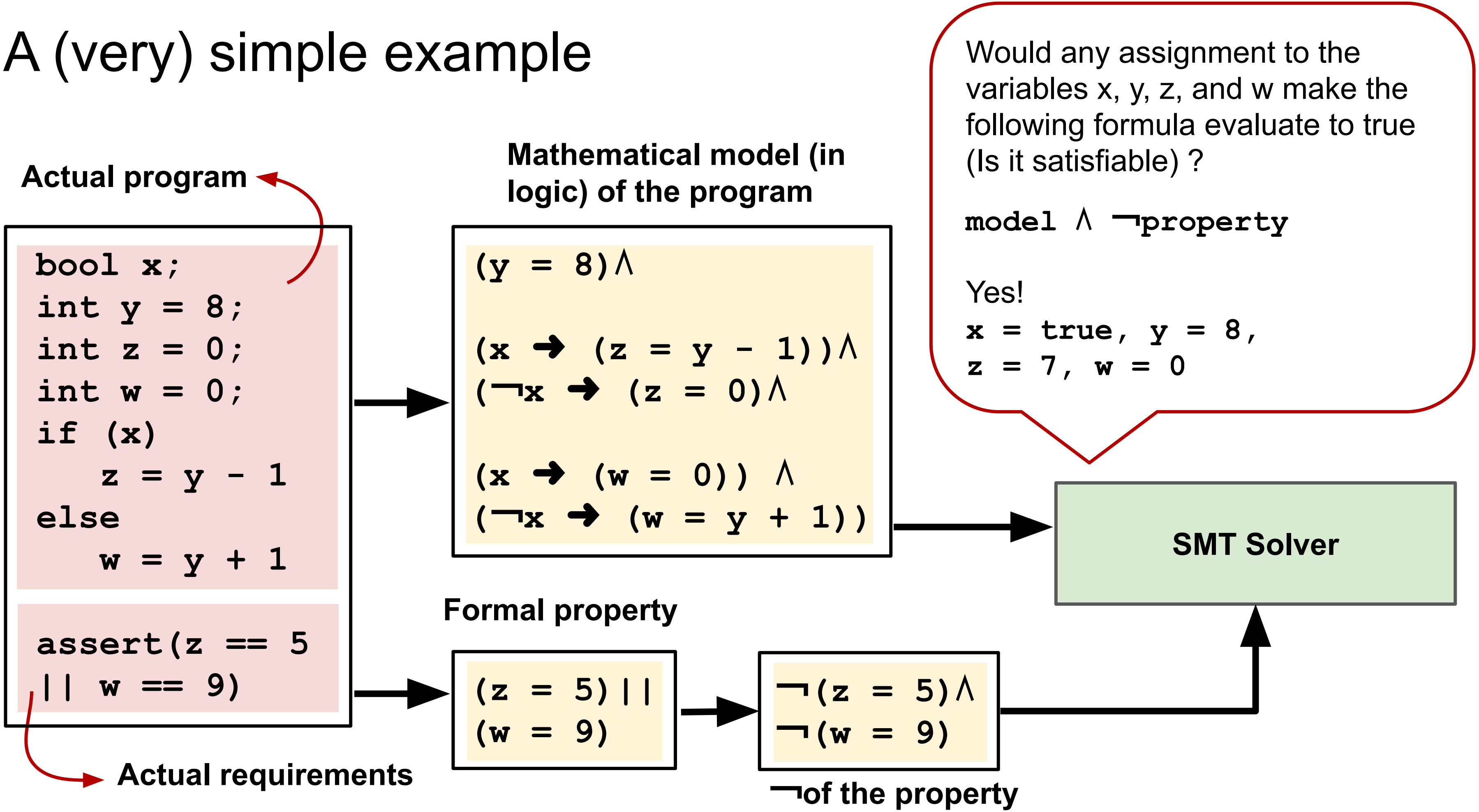

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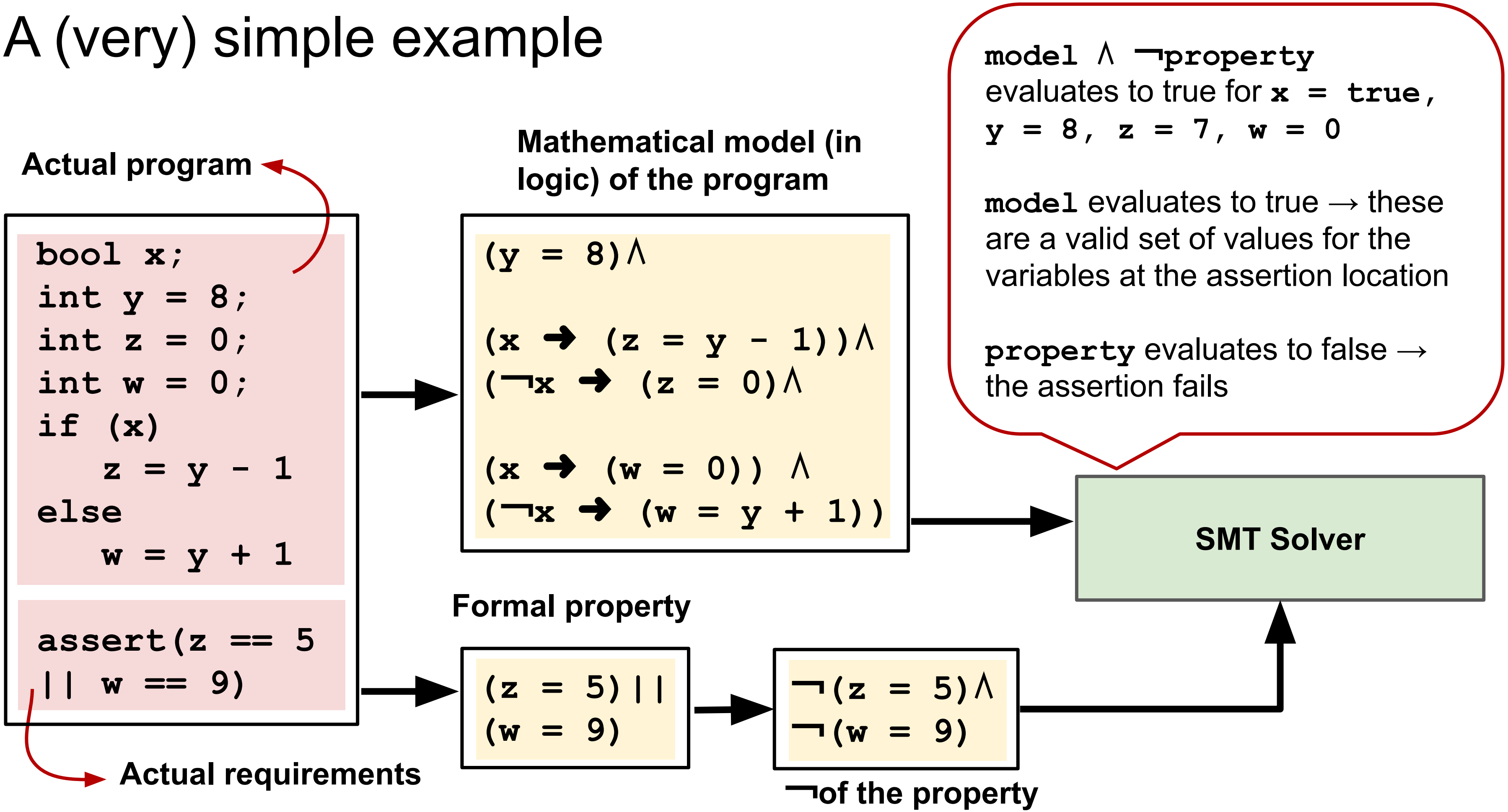

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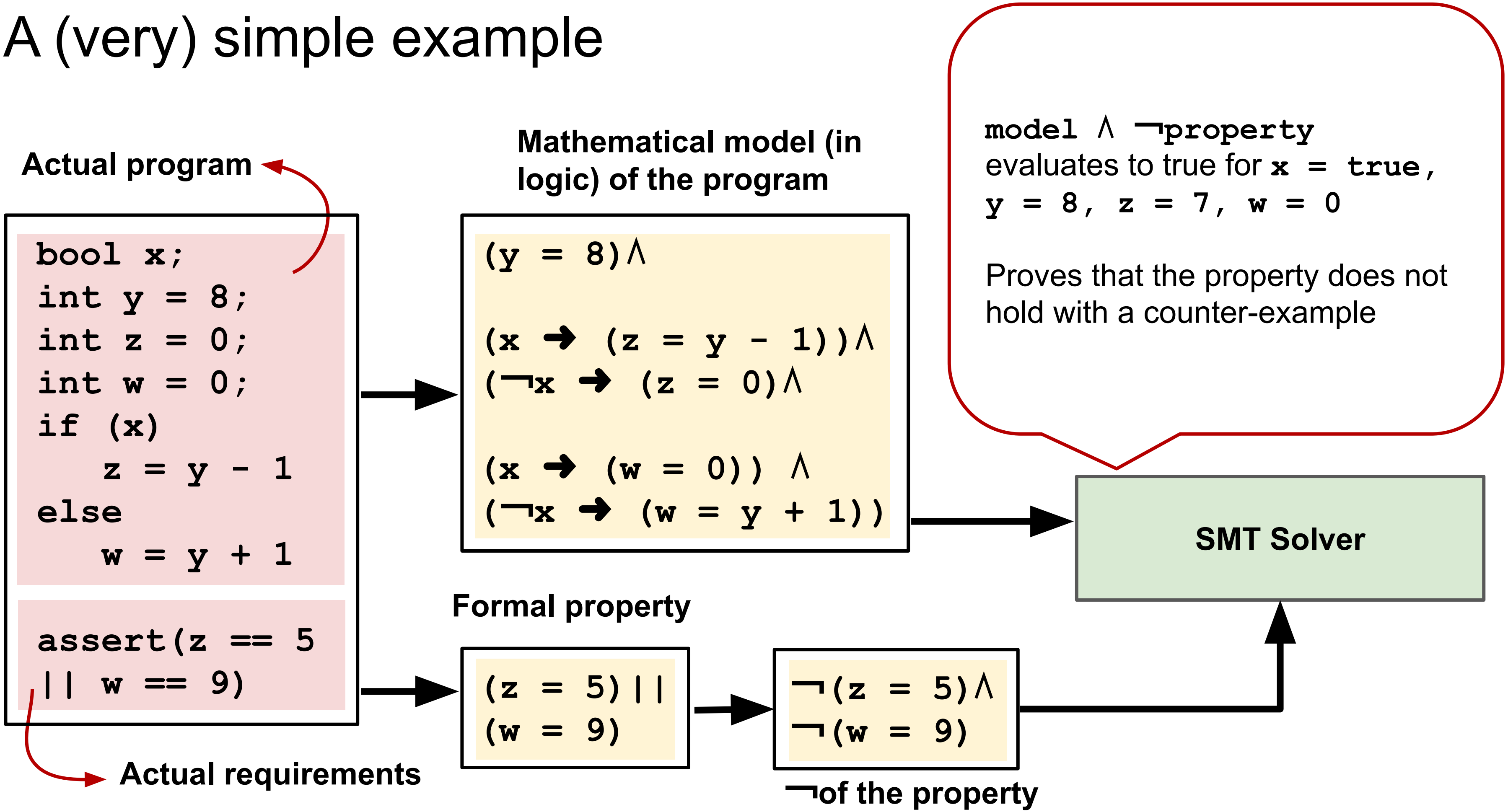

A (very) simple example

Actual program

```
bool x;
int y = 8;
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int w = 0;
if (x)
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```
assert(z == 5
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Actual requirements

A (very) simple example

Actual program

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assert(z == 5
|| w == 9)
```

Let's change this to 7

Actual requirements

A (very) simple example

Actual program

```
bool x;
int y = 8;
int z = 0;
int w = 0;
if (x)
   z = y - 1
else
   w = y + 1
```

```
assert(z == 7
|| w == 9)
```

Actual requirements

A (very) simple example

Actual program

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bool x;
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assert(z == 7
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Actual requirements

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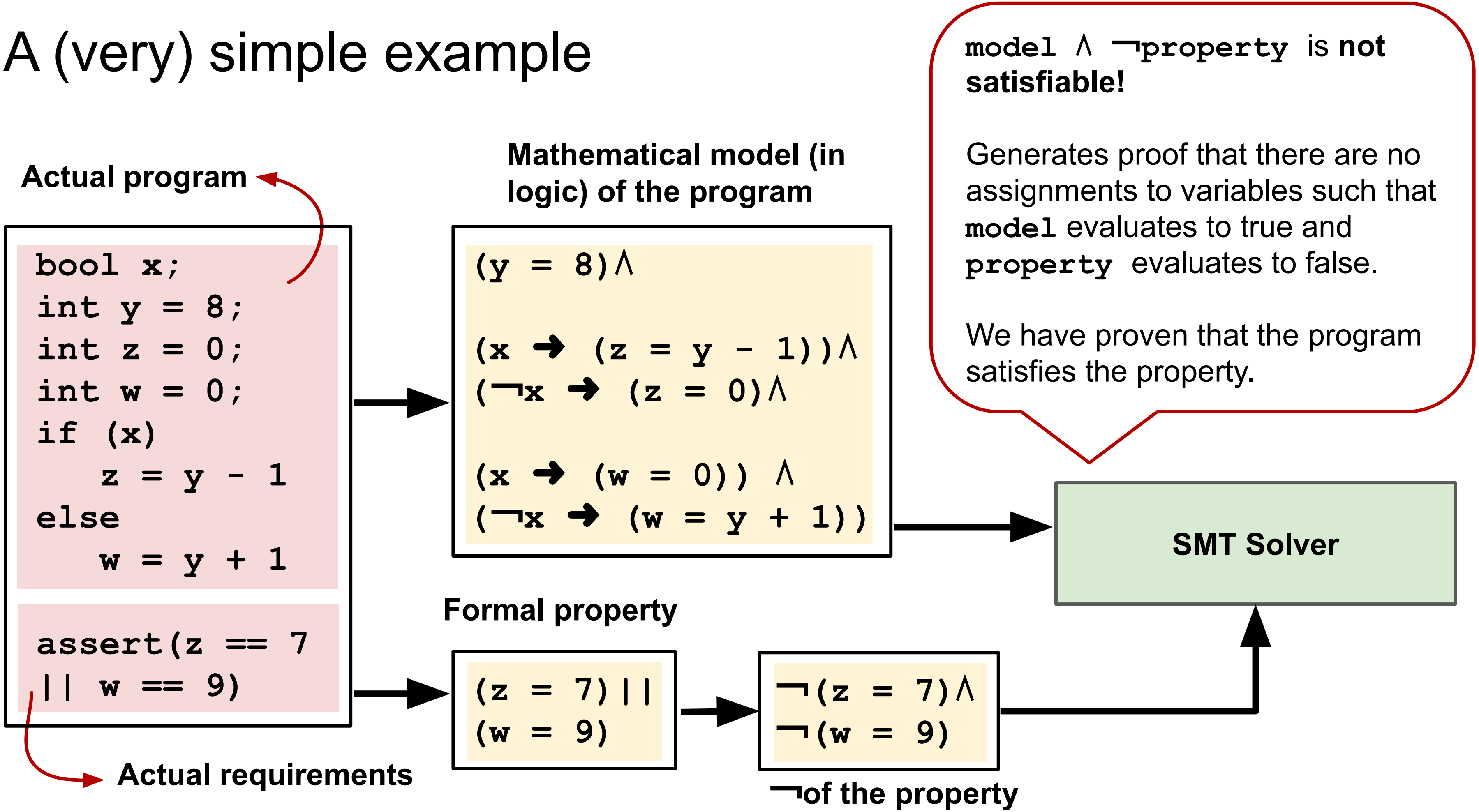

What we haven't talked about (and won't) in this lecture …

- Kripke structures
- Temporal logic
- model checking
- symbolic execution
- Binary Decision Diagrams (BDD)
- Synthesis
- …

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- Kripke structures
- Temporal logic
- model checking
- symbolic execution
- Binary Decision Diagra
- **Synthesis**
- …

Generating a "program" that satisfies a high-level formal specification

- Program synthesis
- Invariant synthesis
- compiler optimizations
- …

Many use cases networking to generate:

- packet processing code for programmable data planes
- configurations and configuration updates
- control-plane repairs
- …

Why use formal verification in networking?

- Networks are growing increasingly complex.
  - They can have hundreds or thousands of interacting components
  - The functionality running in each component is getting more complex
  - configurations files can grow as large as thousands of lines
- Networks are becoming a critical infrastructure
  - Bugs can take down the network or reduce its performance.
  - Network problems can affect thousands if not millions of people
- We need to catch bugs (or prove lack thereof) proactively before going into production

Formal verification in networking

- Started with verifying the forwarding properties of the data plane and control plane.

- Now expanding into more complex functionalities and properties
  - DNS, network performance, …

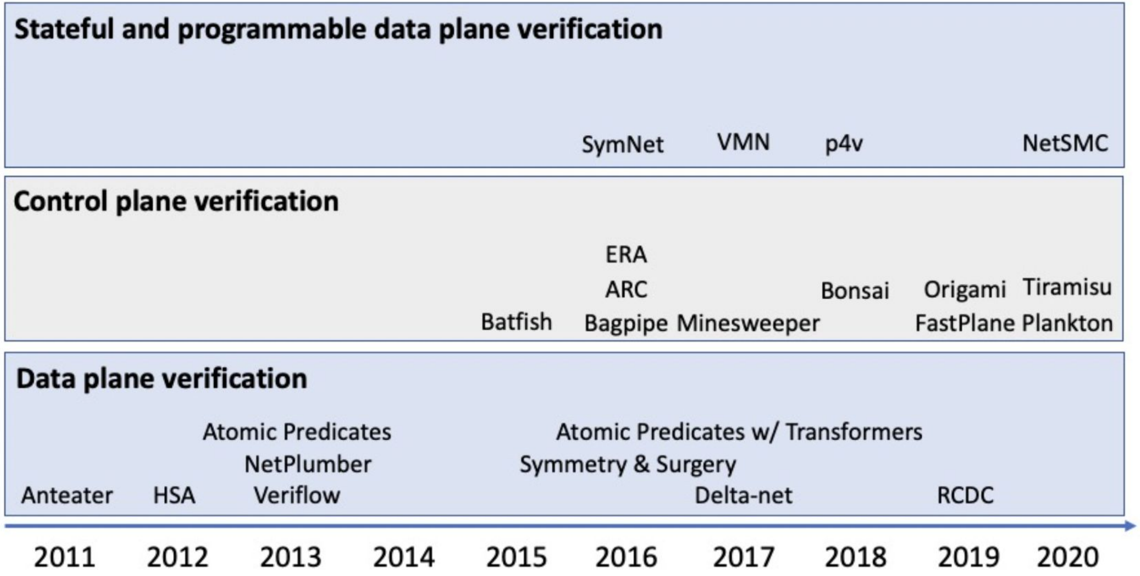

Figure taken from netverify.fun

Formal verification in networking

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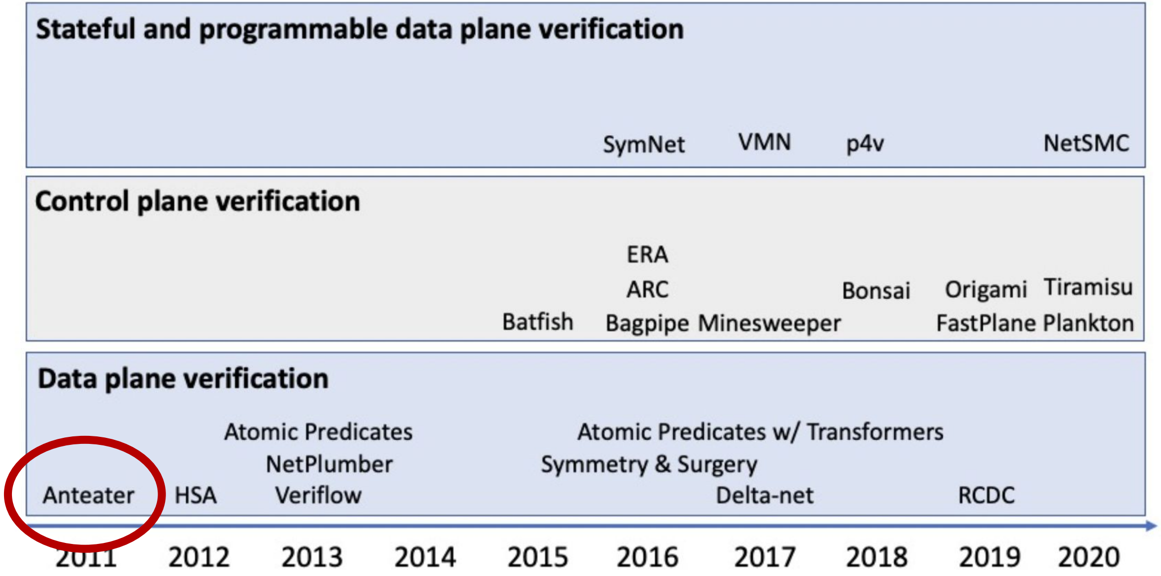
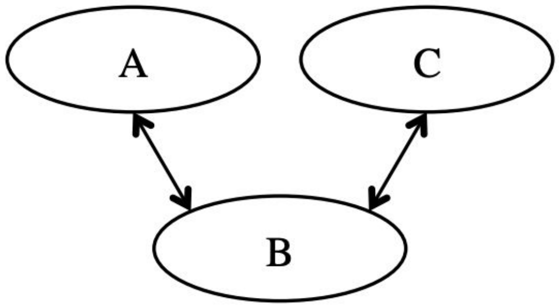


Figure taken from netverify.fun

Example - Anteater (SIGCOMM'11)

- Models the forwarding rule on the data plane as boolean formulas
- Uses a SAT solver to verify invariants about the network behavior
- The invariants are mostly related to forwarding
    - Reachability
    - Absence of forwarding loops
    - Absence of blackholes

Example - Anteater (SIGCOMM'11)



Example - Anteater (SIGCOMM'11)

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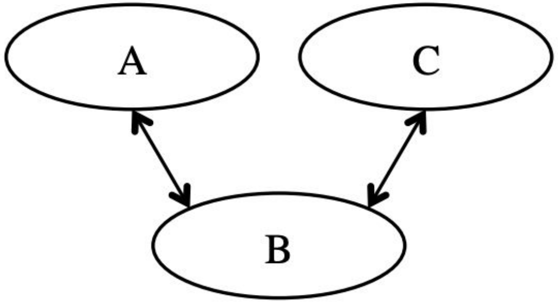

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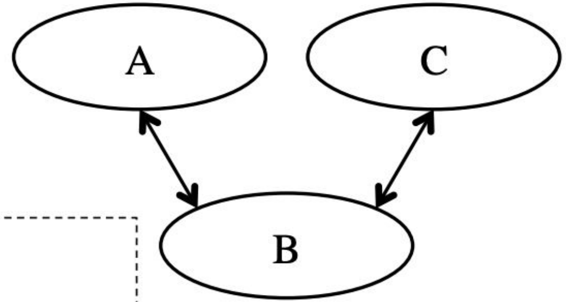

B:
10.1.1.0/24 -> A
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10.1.3.0/24 -> C

B->C:
10.1.3.128/25 -> DROP

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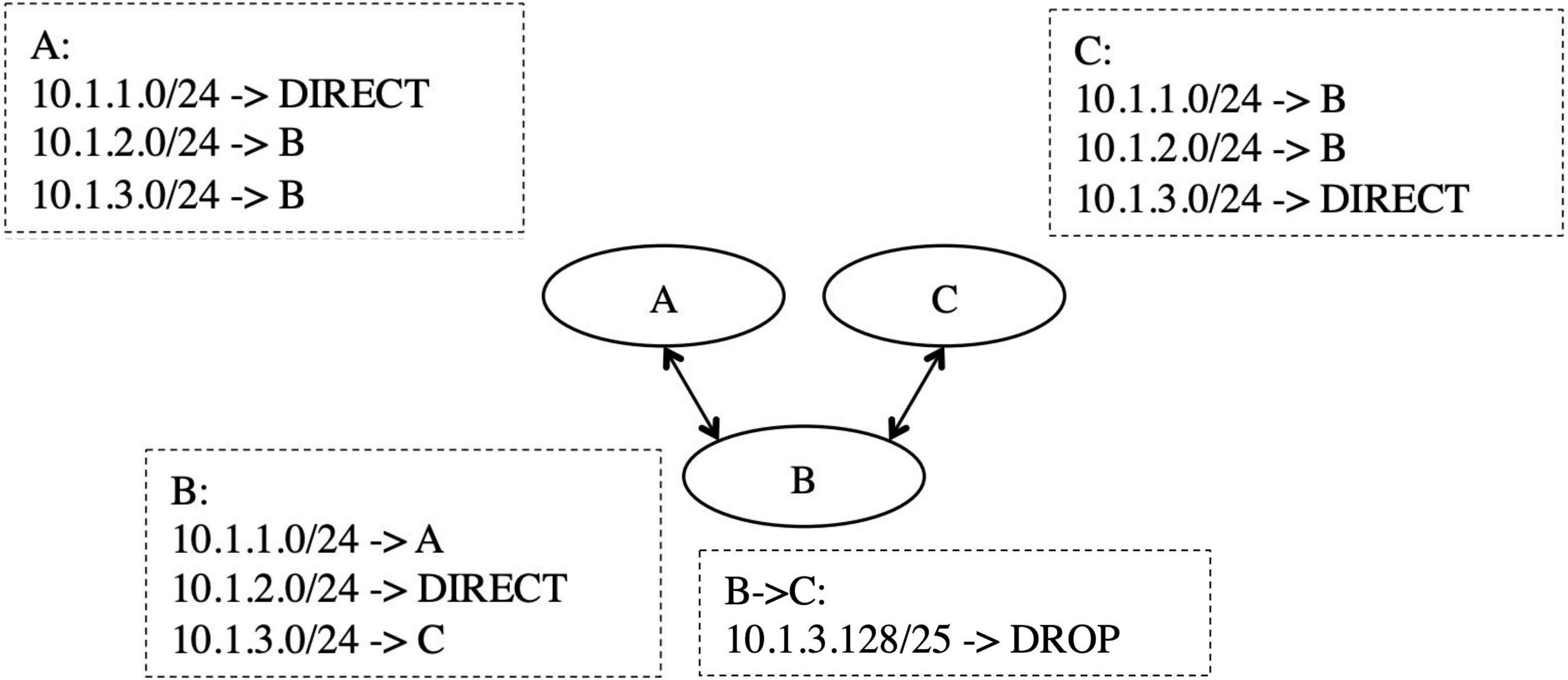

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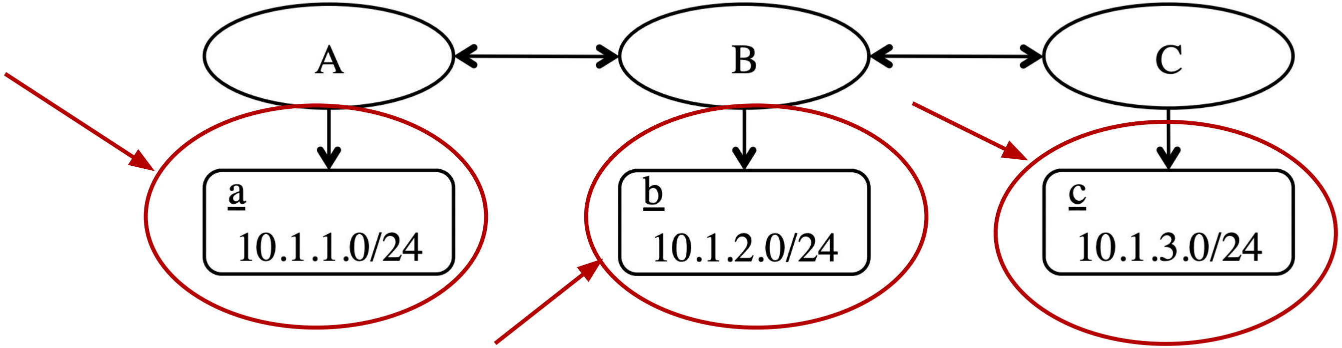

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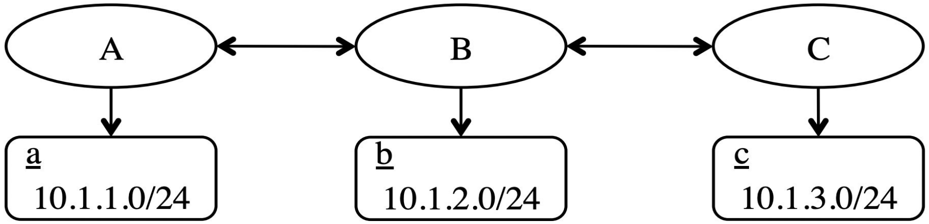

Model each bit in the packet as a boolean variable.

- The rules only use destination IP, so we only model the 32 bits in the destination IP address.

`P(x, y)`: boolean formula describing which packets can go from **`x`** to **`y`**.

Example - Anteater (SIGCOMM'11)

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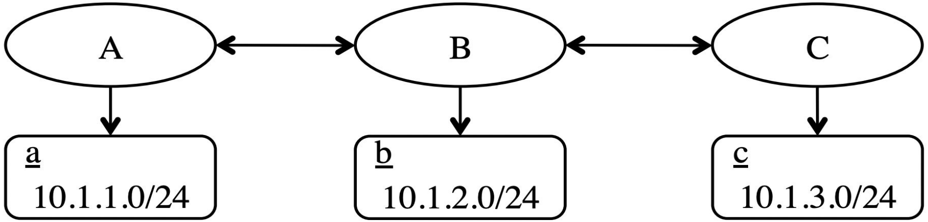
P(x, y): boolean formula describing which packets can go from **x** to **y**.

P(A, a) = dst ip $=_{24}$ **10.1.1.0**

P(A, B) = dst ip $=_{24}$ **10.1.2.0**
$\vee$ **dst ip** $=_{24}$ **10.1.3.0**



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P(x, y): boolean formula describing which packets can go from **x** to **y**.

$$P(A, a) = \text{dst ip} =_{24} 10.1.1.0$$

$$P(A, B) = \text{dst ip} =_{24} 10.1.2.0 \lor \text{dst ip} =_{24} 10.1.3.0$$

$\text{dst ip} =_{w} \text{prefix}$

is a shorthand for

$$\bigwedge_{32-w \le i \le 32} (\text{dst ip}[i] = \text{prefix}[i])$$

Example - Anteater (SIGCOMM'11)

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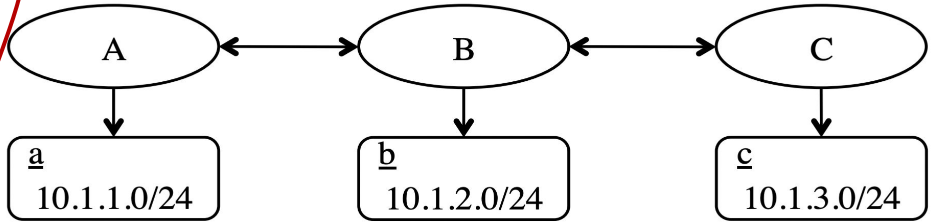

P(x, y): boolean formula describing which packets can go from **x** to **y**.

$\mathtt{P(B,A)} = \mathtt{dst\ ip} =_{24} \mathtt{10.1.1.0}$

$\mathtt{P(B,\ b)} = \mathtt{dst\ ip} =_{24} \mathtt{10.1.2.0}$

$\mathtt{P(B,\ C)} = \mathtt{dst\ ip} =_{24} \mathtt{10.1.3.0}$
$\quad \wedge\ \mathtt{dst\ ip} \neq_{25} \mathtt{10.1.3.128}$

Example - Anteater (SIGCOMM'11)

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C:
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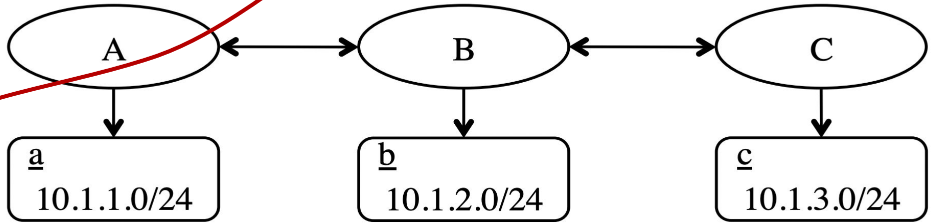


P(x, y): boolean formula describing which packets can go from **x** to **y**.

$$P(C, B) = dst\ ip =_{24} 10.1.1.0 \\ \lor\ dst\ ip =_{24} 10.1.2.0$$

$$P(C, c) = dst\ ip =_{24} 10.1.3.0$$

Example - Anteater (SIGCOMM'11)

- Can A reach C?
- Anteater uses a simple graph algorithm to construct the boolean formula that describe all the packets that can reach C from A using P(x, y)
- That formula is **`P(A, B)`**$\land$ **`P(B, C)`**
- The formula is given to a SAT solver to check if any assignment to the boolean variables, i.e., any destination IP address, exists that can go from A to C
- If no, no packets can reach C from A

Example - Anteater (SIGCOMM'11)

- This was just a simple example
- Anteater shows how to use a similar approach to check for absence of loops and black holes, among other properties.

Reasoning about network forwarding behavior

- Anteater models network behavior as SAT formulas and uses a SAT solver for their analysis.
- Since then, there has been several other proposals for other ways for both modeling and analysis

Reasoning about network forwarding behavior

- Since then, there has been several other proposals for other ways for both modeling and analysis
- Header Space Analysis (HSA) (NSDI'12)
  - models sets of K-bit packets as subspaces in a K-dimensional space
  - uses set operations for analysis
- Veriflow (NSDI'13)
  - uses a trie to find equivalence classes (ECs) of packets
  - models the forwarding behavior of ECs using a forwarding graph
  - analyzes the network behavior using graph algorithms
- There has been a lot more! (see netverify.fun for a survey)

Formal methods in networking

- Data-plane verification
  - Model and analyze the forwarding rules on the data plane
  - Anteater, HSA, Veriflow, …
- Control-plane verification
  - Model and analyze the control-plane protocols that configure the data plane
- Stateful and programmable data planes

Formal methods in networking

- Analyzing DNS
  - Is there a query under our domain that is sent for resolution to a name server, not under our domain?
- Analyzing performance
  - Is there an input traffic pattern under which the network provides high latency?

Formal methods in networking industry

- Large cloud providers are integrating formal methods into their network operations
  - Microsoft, Amazon, Google, Alibaba, …
  - "Be sure before shipping – the need for safety in clouds" - Dave Maltz keynote in the netverify'21 workshop organized by Microsoft and Google
- Several startup companies
  - Forward Networks, Veriflow, Intentionet, …

How does this all relate to programmable networks?

- Automated testing and verification did not start with and is not limited to programmable networks.
- But, programming abstractions for a single device or collection of devices provides extra opportunities.
  - We can reuse so much of the existing knowledge, expertise, and tools for program verification in the formal methods and PL community
  - In our "network" programs, we already have accurate well-defined specifications of network functionality.
  - We can verify the compilers (or their output) to provide end-to-end verified tool chains
  - …

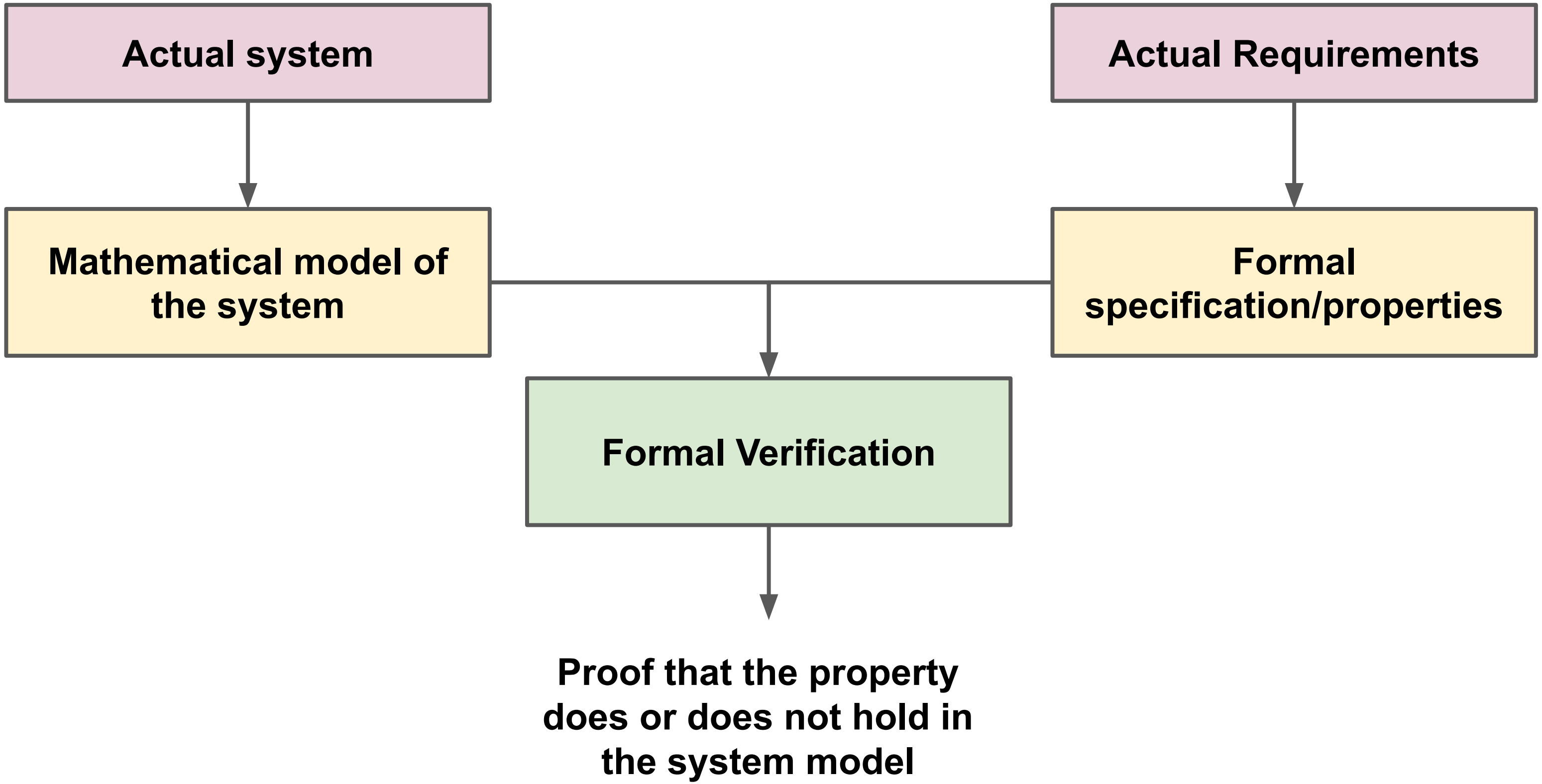
What's next?

- So far, we have convinced ourselves that using formal methods in networking is both essential and possible
- Now, we need to make it usable in a more widespread manner in real-world networks.
- What is missing?

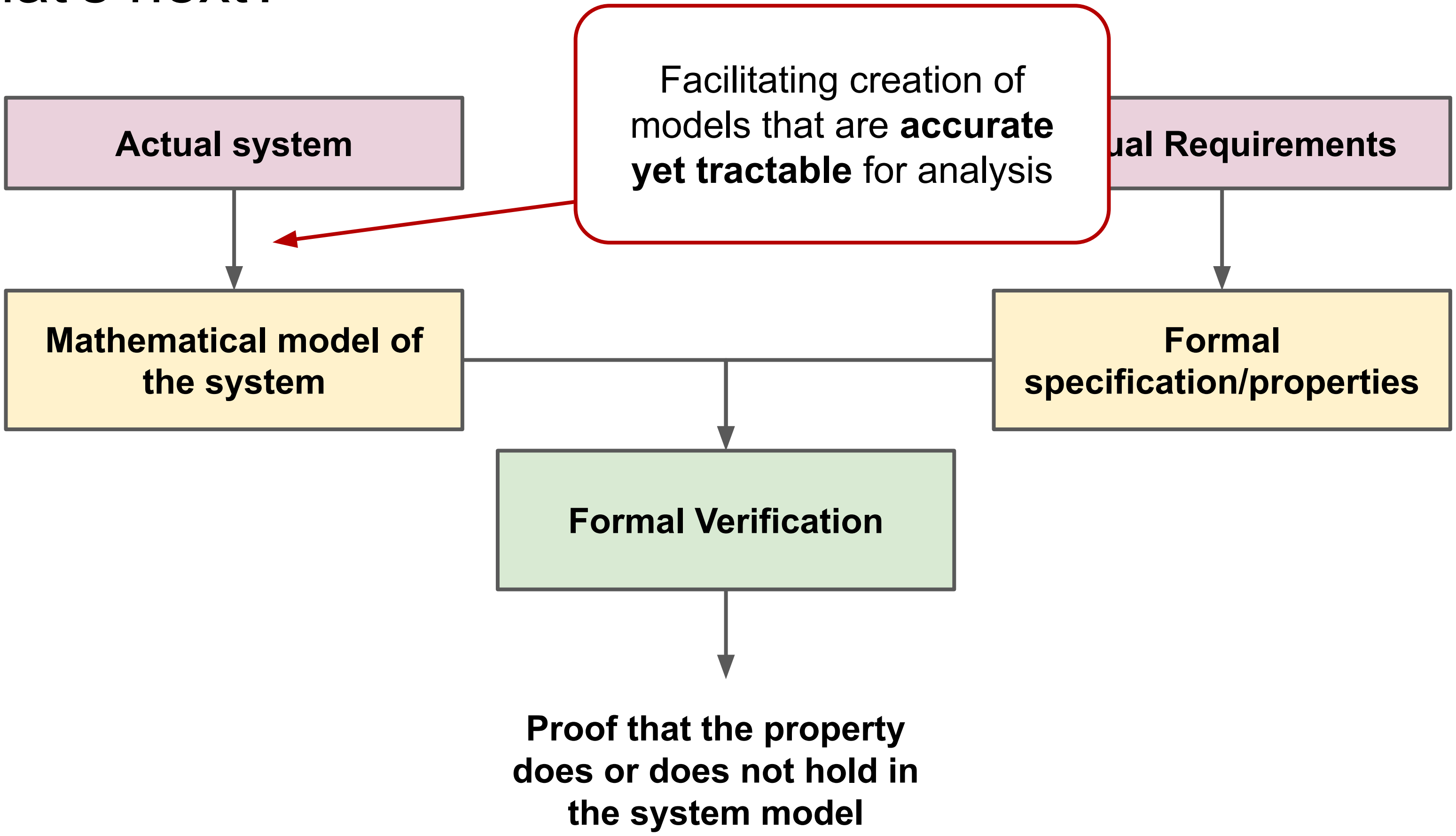
What's next?

- Scale
  - Formal methods tools don't scale well :)
  - There is evidence that they can scale to large network for certain networks and certain properties with lots of optimizations
  - One way forward is "modular" verification, where we verify smaller subsets of the network independently and then combine the results.
  - So, there is hope but also still a long way to go
- Functionalities and properties beyond forwarding
  - network functions, network performance, …

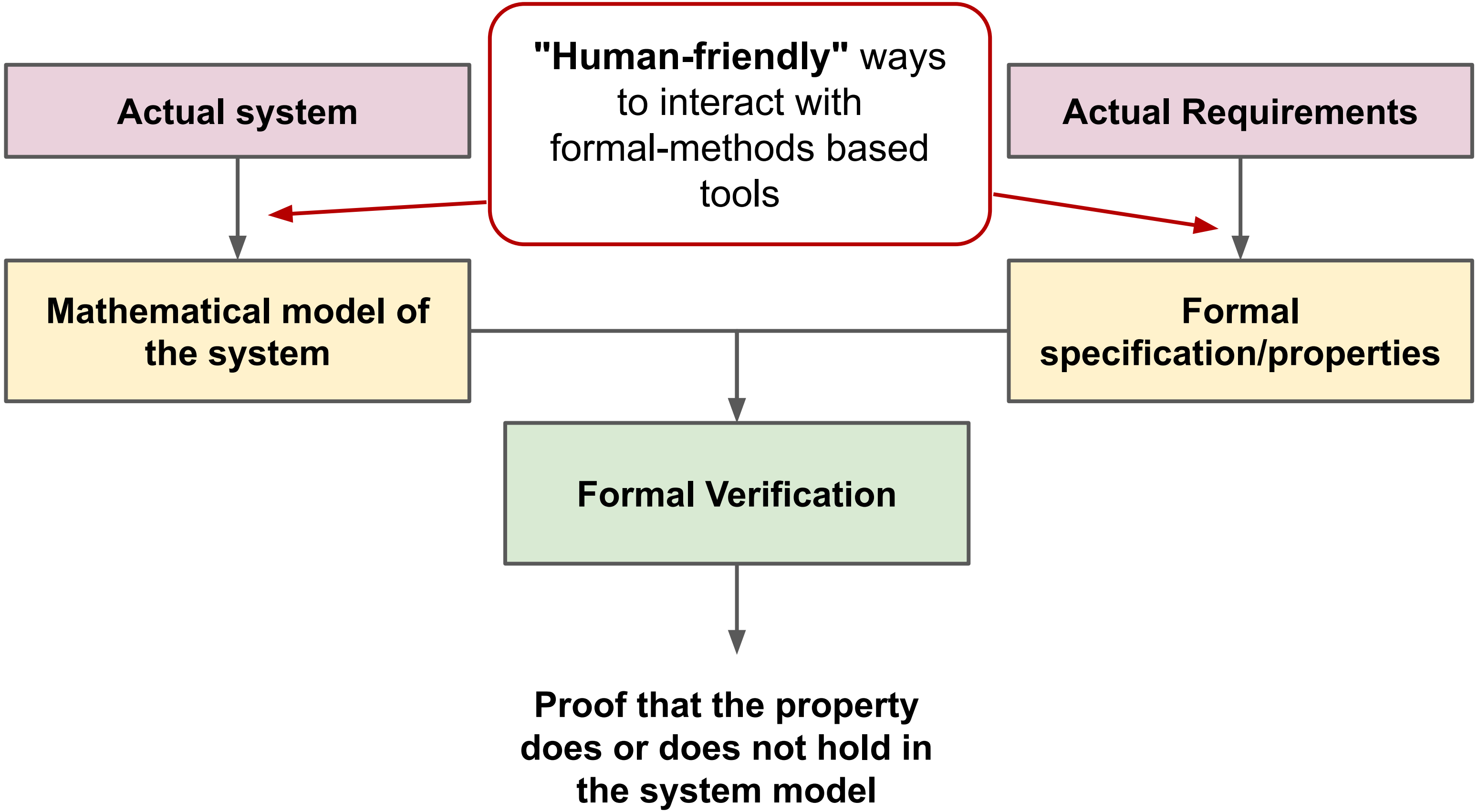
What's next?


Actual system
Actual Requirements
Mathematical model of the system
Formal specification/properties
Formal Verification
Proof that the property does or does not hold in the system model

What's next?


Actual system
Facilitating creation of models that are **accurate yet tractable** for analysis
ual Requirements
Mathematical model of the system
Formal specification/properties
Formal Verification
Proof that the property does or does not hold in the system model

What's next?



Actual system
"Human-friendly" ways to interact with formal-methods based tools
Actual Requirements
Mathematical model of the system
Formal specification/properties
Formal Verification
Proof that the property does or does not hold in the system model

Paper 1: p4v: Practical Verification for Programmable Data Planes

- A tool for verifying properties about P4 programs
  - General safety properties, e.g., avoiding read/writes to invalid headers
  - Program-specific properties specified using assert statements
- Has to work around the fact that the some data-plane rules come from the control plane and are only known at run-time

Paper 2: Validating Datacenters At Scale

- Describes the tools used in Microsoft Azure's network for verifying ACLs and forwarding rules
- To scale, they use domain-specific insights to simplify the analysis
    - Structural properties of the topology
    - Decompose what they want to validate into checks on local devices
    - …

Additional Resources

- netverify.fun
  - History and survey of verification tools
  - Articles from experts about what's new in the area
- Network verification and synthesis course from University of Washington
- Papers on analyzing DNS and performance, among others