MODEL-BASED GREY-BOX FUZZING

“Fuzzing the Shall-Nots”

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TALK OVERVIEW

- **Model-Based Test Generation and Fuzzing**
- Testing –vs- Fuzzing
- Environmental Models
- Fuzzing Requirements Framework
- Fuzzing for Credit

MODEL-BASED TEST GENERATION

- Given:
  - A Model of the System (Requirements)
  - Simulink, SpeAR, DSL
  - Mathematical Description
- Objective:
  - Generate Tests that Satisfy Stringent Coverage Criteria
  - Multiple-Condition/Decision-Coverage (MC/DC)
- Methodology:
  - Express Testing Objectives as Logical Constraints
  - Generate Tests Using Constraint Solver

- Historically Labor Intensive Activity
- High-Coverage Tests Generated Automatically (from Requirements)

CREW ALERTING SYSTEM: PROBLEM

- The logic for displaying a CAS message driven by complex Boolean equations
- Each airplane program contains a thousand or more such equations and each need to be thoroughly tested
- Example:

```
ID: TENC_OIL_PRESS_SB1
Logic:
    TDT2S.SB1_PRESS_LOW OR
    TDT2S.SB1_PRESS_HIGH OR
    TDT500MS.(SB1_PRESS_LOW AND SB1_PRESS_HIGH);

Inhibit: LANDING
^**
```

- The complexity of CAS equations can be overwhelming:
  - Contain numerous logical conditions (not unusual for 10 or more to appear in an equation)
  - Reference other equations
  - Reference previous versions of variables, including the equation other test.
  - May be inhibited by other equations

“Formal Methods for Certification”, Lucas Wagner

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CREW ALERTING SYSTEM: IMPACT

Model Based Test Generation

- Constraint solver employed to generate tests that satisfy "MC/DC" coverage metric.
- Generated thousands of tests covering ~95% of equations under test.

Future:

- Test generator is scheduled for use on every program as standard work.

Table A-7 Verification of Verification Process Results

	Objective		Activity	Applicability by Software Level				Output		Control Category by Software Level			
	Description	Ref	Ref	A	B	C	D	Data Item	Ref	A	B	C	D
1	Test procedures are correct.	6.4.5.b	6.4.5	●	○	○		Software Verification Results	11.14	②	②	②	
2	Test results are correct and discrepancies explained.	6.4.5.c	6.4.5	●	○	○		Software Verification Results	11.14	②	②	②	
3	Test coverage of high-level requirements is achieved.	6.4.4.a	6.4.4.1	●	○	○	○	Software Verification Results	11.14	②	②	②	②
4	Test coverage of low-level requirements is achieved.	6.4.4.b	6.4.4.1	●	○	○		Software Verification Results	11.14	②	②	②	
5	Test coverage of software structure (modified condition/decision coverage) is achieved.	6.4.4.c	6.4.4.2.a 6.4.4.2.b 6.4.4.2.d 6.4.4.3	●				Software Verification Results	11.14	②			
6	Test coverage of software structure (decision coverage) is achieved.	6.4.4.c	6.4.4.2.a 6.4.4.2.b 6.4.4.2.d 6.4.4.3	●	●			Software Verification Results	11.14	②	②		
7	Test coverage of software structure (statement coverage) is achieved.	6.4.4.c	6.4.4.2.a 6.4.4.2.b 6.4.4.2.d 6.4.4.3	●	●	○		Software Verification Results	11.14	②	②	②	
8	Test coverage of software structure (data coupling and control coupling) is achieved.	6.4.4.d	6.4.4.2.c 6.4.4.2.d 6.4.4.3	●	●	○		Software Verification Results	11.14	②	②	②	
9	Verification of additional code, that cannot be traced to Source Code, is achieved.	6.4.4.c	6.4.4.2.b	●				Software Verification Results	11.14	②			

"Formal Methods for Certification", Lucas Wagner

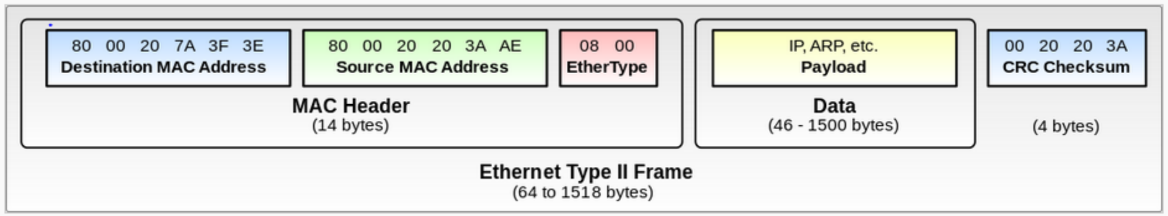
FUZZING (FUZZ TESTING)

- Robustness Testing
  - Apply Random, Invalid or Unexpected Inputs
- Monitor Health of System
  - Exceptions, Lock-Up, Memory Usage, Power Consumption, etc.
- Anomalous Behavior
  - May Reveal Exploitable Vulnerability
  - Record Inputs for Later Forensic Analysis
- Cyber Grand Challenge
  - Fuzzing Used Extensively for Automated Penetration Testing

> The original work was inspired by being logged on to a modem during a storm with lots of line noise. And the line noise was generating junk characters that seemingly was causing programs to crash. The noise suggested the term "fuzz".
>
> --Barton Miller, University of Wisconsin (1988)

SMART FUZZING

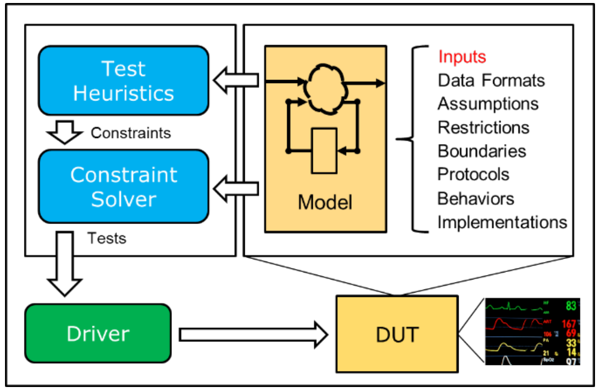
- Smart Fuzzing Frameworks
  - Sulley, Peach, scapy
- Format Specifications (Templates)
  - Random Inputs are “Constructed” by filling in blanks in Templates
- Enables Detection of Deeper Bugs
  - Passes CRC Check

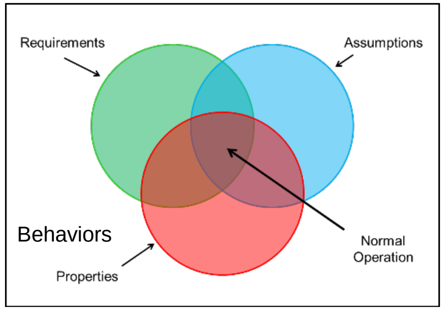


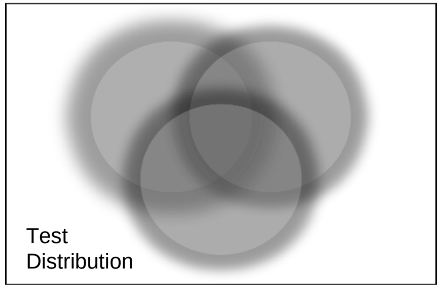
The most common Ethernet Frame format, type II

MODEL-BASED FUZZING

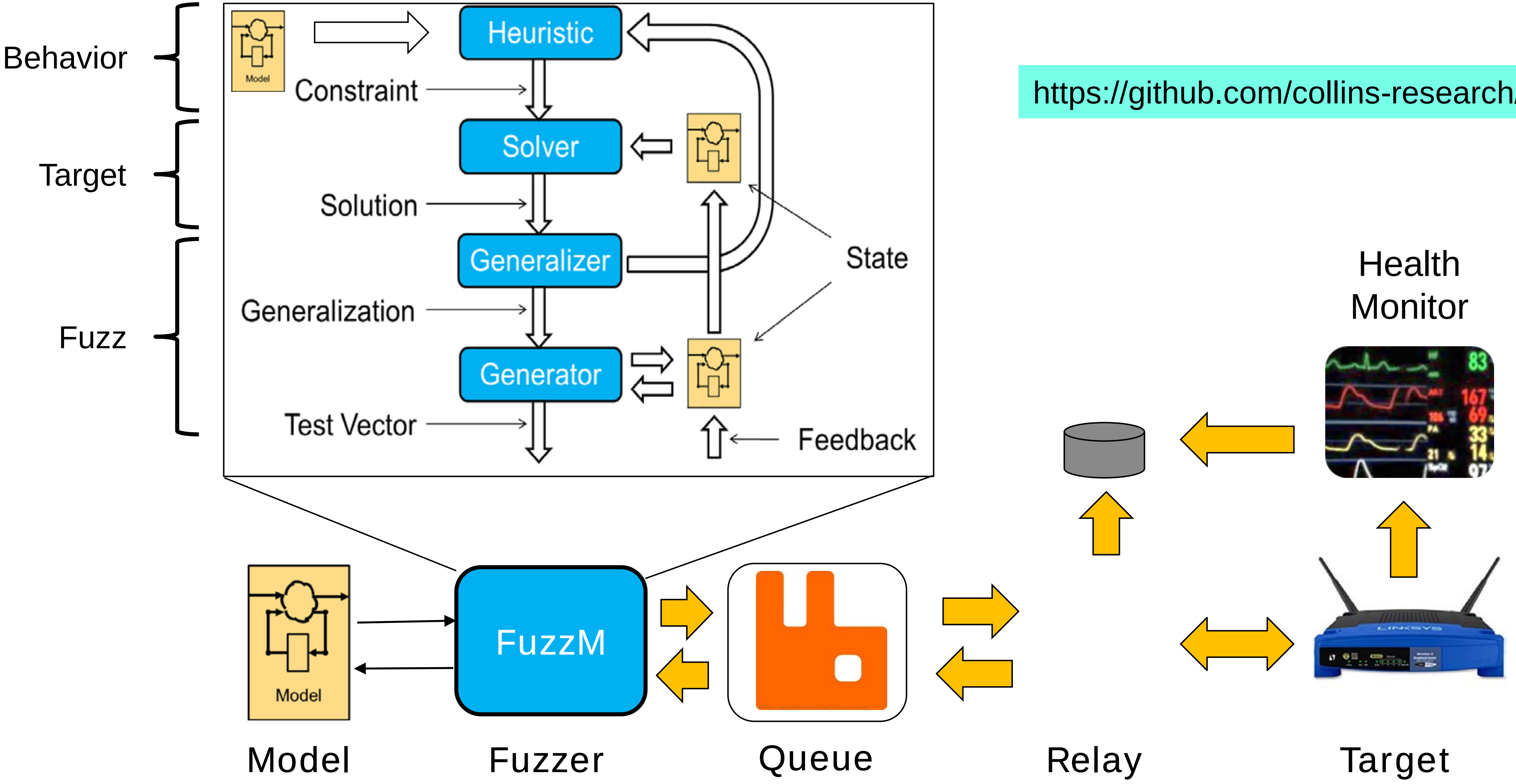
- *Model* Describes Fuzzing Target
  - Description Includes Behavior
    - Not Just Data Formats
  - Can Describe Stateful Behaviors
    - Fragment/Reassemble Message
- *Constraint Solver* Generates Tests
  - Tests are “Deduced”, not “Constructed”
  - Constraints capture “Interesting Behaviors”
- Constraint Solving + Fuzzing
  - Solver **Targets** Behaviors we **Know**
  - Fuzzer **Explores** Behaviors we **Don’t Know**







FUZZM COMPONENT ARCHITECTURE



https://github.com/collins-research/FuzzM

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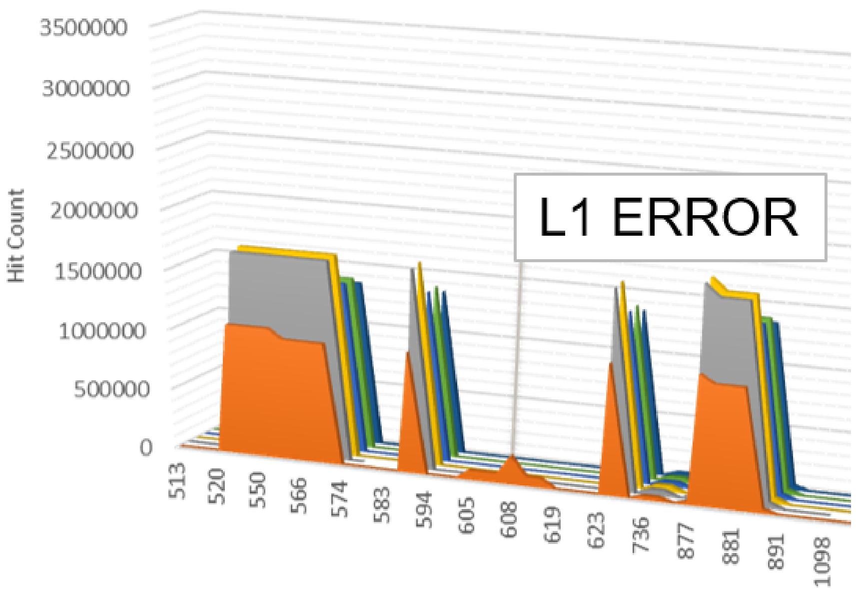
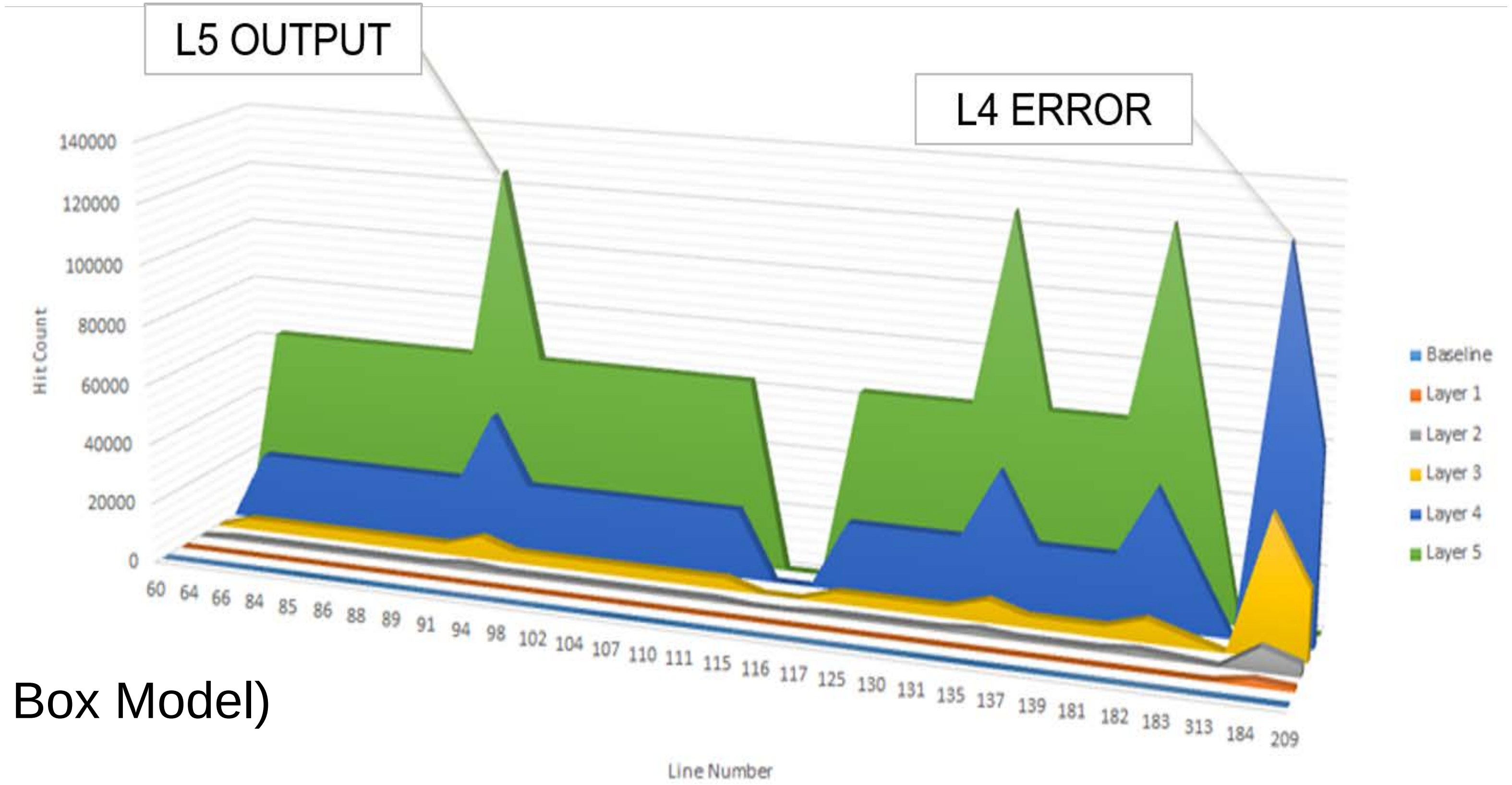
LAYERED REQUIREMENTS MODEL

OSI Model				
Layer			Protocol data unit (PDU)	Function[3]
Host layers	7	Application	Data	High-level APIs, including resource sharing, remote file access
	6	Presentation		Translation of data between a networking service and an application; including character encoding, data compression and encryption/decryption
	5	Session		Managing communication sessions, i.e. continuous exchange of information in the form of multiple back-and-forth transmissions between two nodes
	4	Transport	Segment, Datagram	Reliable transmission of data segments between points on a network, including segmentation, acknowledgement and multiplexing
Media layers	3	Network	Packet	Structuring and managing a multi-node network, including addressing, routing and traffic control
	2	Data link	Frame	Reliable transmission of data frames between two nodes connected by a physical layer
	1	Physical	Symbol	Transmission and reception of raw bit streams over a physical medium

LAYERED MODEL COVERAGE RESULTS





Baseline : No Requirements (Black Box Model)

…

Layer 5 : Complete Requirements Model

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FUZZER COVERAGE COMPARISONS

AFL Boofuzz Hongfuzz Radamsa FuzzM

Missed Coverage

Unique Coverage

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TESTING –VS- FUZZING

Testing

- Methodology
  - Apply (Crafted) Inputs
  - Measure Outputs
    - Compare against expected Oracle
- Abstraction
  - Underspecified Behavior
  - “Oracle Equality” Challenging

Fuzzing

- Methodology
  - Apply (Random) Inputs
  - Monitor Health
    - Compare against Nominal Behavior
- Relaxed Oracle
  - Makes Fuzzing “Easier”
- If Fuzzing Violates Assumptions
  - Behavior is Unspecified
  - “Testing” is not possible

TESTING –VS- FUZZING

Testing

- Keys to Success
  - Strong Controllability
  - Strong Observability
  - Precise Oracle

Fuzzing

- Challenges
  - Controllability
  - Observability
  - Oracle Precision (Health)

TESTING –VS- FUZZING

Testing

- Limited Test Suite
  - Certification Tests
    - Cost of Development
    - Cost of Maintenance
    - Cost of Traceability
  - Production/Acceptance Tests (HW)
    - Cost of Test Evaluation Time
- Testing Metrics
  - Proxy for Effectiveness
  - Trade Quality for Quantity

Fuzzing

- “Unlimited” Test Suite
  - Fuzz and Forget
  - Continuous Integration
  - Production Testing
    - Offers little or no value
    - Not Detecting Manufacturing Defects
  - Acceptance Tests (?)
- Fuzzing Metrics
  - No Standard Metrics
  - Trade Quantity for Quality (?)

TESTING –VS- FUZZING

Testing

- SHALL
  - Typifies “Safety Requirement”
  - Property
    - forall (x): good(x)
  - Test
    - good(x0)
    - some (x): good (x)

Fuzzing

- SHALL NOT
  - Typifies “Security Requirement”
  - Property
    - not exists (x): bad(x)
      - forall (x): not bad(x)
  - Test
    - some (x): not bad(x)
  - Fuzz
    - foralot (x) : not bad(x)

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MODEL-BASED FUZZING

- How does it differ from model (requirements) based test generation?
- What constitutes a fuzzing model?
- How does it compare to existing MDB artifacts?

REQUIREMENTS, ASSUMPTIONS AND OPERATING ENVIRONMENT

- Requirement Specifications
  - **Typically Include Assumptions**
  - Embedment Manual
    - Where and How can this system be used?

- Assumptions Constrain the **Environment**
  - We Found a Bug .. Here is the Trace!
    - **"That Would Never Happen In-System"**
      - .. but what if it does?
  - Assumptions Restrict the **Threat Model**

FUZZING STRAINS ENVIRONMENTAL MODELS

- Basic (Random)
  - Env. Assumption : Variable Bounds
  - Fuzzing Objective : Boundary and Combinatorial Testing
- Safety (Murphy)
  - Env. Assumption : Operational Envelope
  - Fuzzing Objective : Robustness
- Security (Malicious)
  - Env. Assumption : Deployment Threats/Risks
  - Fuzzing Objective : Resiliency

THE BAD-GUY

- Quantification in 1st order Logic
  - Replace quantified variable
  - With a function (skolem)
    - Not just any function ..
    - The “bad-guy” function
  - If there is a problem input
    - this function will find it!

- The bad-guy function
  - Aware of the “model”
  - Aware of the desired property
  - Computes “worst possible” value

- If property is true for bad-guy
  - The property is true for all inputs

forall (x) : not bad(x)

```
(iff (list-equiv x y)
     (and (equal (len x) (len y))
          (forall (a) (equal (nth a x) (nth a y)))))
```

```
(local
 (defun list-equiv-bad-guy (x y)
   (if (and (consp x) (consp y))
       (if (not (equal (car x) (car y))) 0
         (1+ (list-equiv-bad-guy (cdr x) (cdr y))))
     1)))

(local
 (defthm list-equiv-reduction
   (iff (list-equiv x y)
        (and (equal (len x) (len y))
             (equal (nth (list-equiv-bad-guy x y) x)
                    (nth (list-equiv-bad-guy x y) y))))
   :hints (("Goal" :in-theory (enable nth)))))
```

“**FUZZING MODELS**” ARE “**ENVIRONMENTAL MODELS**”

- The Most **Formidable** Environmental Models
  - Include a Model of the **Target** System
    - The Protocol it Speaks
    - The Mode it is In
    - The Input it Expects
  - Knowledge of the Target
    - Enables Effective “Attacks”
    - Bad-Guy
  - Murphy and Malicious Models
    - Will Always Have This Flavor
  - Still: Not Simply Unconstrained

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REQUIREMENTS SPECIFICATION IN SPEAR

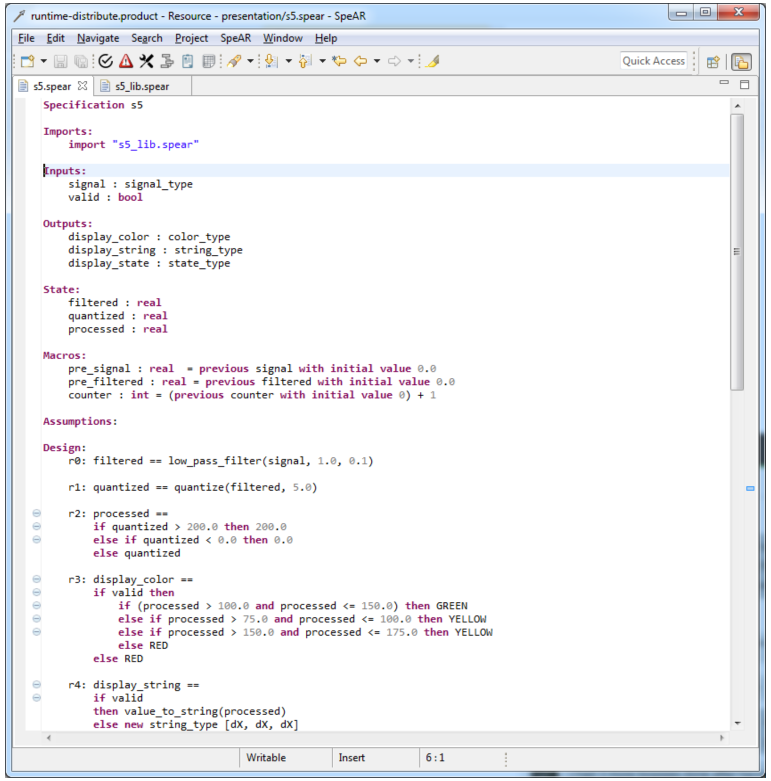
SpeAR =

Specification and **A**nalysis of **R**equirements

An Integrated development environment for formally specifying and rigorously analyzing requirements.

- Eclipse-based, Xtext language
- Formal methods driven analyses

- A specification language that's expressive as possible while still analyzable using state-of-the-art model checking tools.



https://github.com/lgwagner/SpeAR

SPEAR CORE CAPABILITIES

SPECIFICATION

Rich (as possible) specification language for formally describing how a system should operate.

- supports temporal predicates for describing event ordering
- type system that allows for efficient behavioral specification
- well-formedness checking
- supplemental static analyses

ANALYSES

A set of analyses to establish correctness, completeness, and consistency of requirements sets before actually building the system.

- logical entailment
- consistency and realizability
- traceability

FuzzM Integration

- UFC-Based Fuzzing Constraints
- Selectively Relaxed Assumptions

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FUZZING IN THE LARGE

- Fuzzing Has Proven Effective
  - Finds Many Kinds of Issues
  - Implementation
    - Bugs in Corner Cases
  - **Requirements**
    - **Unintended/Emergent Behaviors**
    - Requirements (Assumption) Validation
  - Forces Consideration
    - Of Additional Use Cases
  - Fuzzing Can be “Cheap”
    - Fuzz and Forget

- Model-Based Fuzzing
  - Leverages, Extends MBD Paradigm
    - Constrained, Formidable Environmental Models
  - Automated Fuzz Test Generation
    - Targets Interesting Behaviors
  - Comparable to white-box fuzzing
    - Complete Requirements

FUTURE: FUZZING FOR CREDIT

- Emerging Security Certification Standards
  - Proposed ASISP amendment 14 CFR 25
  - Proposed EASA amendment 2019-01

- Measurements for Security
  - Effectiveness arguments often lack Rigor
  - Lacks Quantitative Measures

- **Fuzzing will Eventually be Part of the Assurance Story**
  - Safety
    - Robustness
  - Security
    - Resiliency
  - To Compete with Testing
    - Needs Rigor, Quantitative Measures

Fuzzing the Shall-Nots

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Questions?