Hasso Plattner Institut
IT Systems Engineering | Universität Potsdam

An Error Model for Multi-threaded Single-node Applications, and Its Implementation

Lena Feinbube, Daniel Richter, and Andreas Polze

Operating Systems & Middleware Group
Hasso Plattner Institute at University of Potsdam, Germany

Reality...

- usual assumption:
  - linear relationship between faults, errors, and failures
- but...
  - relation between faults, errors, and failures is complex
  - consequences of a bug are arbitrarily related in time, space, and severity to the cause
  - error state may arise only if multiple faults are activated under certain conditions
  - several error states may necessary for a system failure
  - interaction between multiple software components frequently accounts for software outages

Motivation

- fault injection: testing complex software system's fault tolerance and overall dependability
  - artificially inject fault & error states into running system
  - observe how well these situations are handled
- one central question: **which** faults and error states to inject, and **when**?
- failure cause model: describes what is injected (into running program)
- need for a realistic failure cause model
- faultload representativeness

Motivation

- fault injection testing at interfaces is powerful
- **Hovac**
  - dependability benchmarking & fault injection tool
  - orchestrates fault injection campaigns
  - repeatable & configurable
  - injection at interface level (function calls to external libraries)
  - failure-cause model: misbehavior of external, third-party code
  - implementation: dll API hooking (*Detours* library)

Lena Herscheid, Daniel Richter, and Andreas Polze, “Hovac: A configurable fault injection framework for benchmarking the dependability of C/C++ applications,” in *2015 IEEE International Conference on Software Quality, Reliability and Security, QRS 2015, Vancouver, BC, Canada, August 3-5, 2015*, 2015, pp. 1–10.

Motivation

- Common Weaknesses Enumeration (CWE) Database (by Mitre)
  - classify all kinds of software weaknesses
    - i.e. programming language, severity, kinds of error states
  - provides realistic failure data
  - based on experiences of research & industry
- realistic fault injection experiments:
  failure cause models should base on such community-gathered empirical data

Motivation

- **our contribution**: error model for dependability benchmarking with Hovac; error classes derived from CWE database

requirements for fault injection error model:

- formality
  - existing error descriptions (bug reports, commit messages): anecdotal, textual descriptions of error state leading to failure
  - aim: more formal definition, less specific

Motivation

requirements for fault injection error model (contd.)

- executability
  - possibility to implement for fault injector
  - execution triggers the desired error state
  - ideal: non-intrusive, applicable to arbitrary software, general & application specific error states
- realism
  - asses the quality of fault-tolerance mechanisms: only useful if faults and error states correspond to real world problems

Agenda

- research gap outline
- error classes derived from CWE database
- abstract formalization of such errors
  - concepts: state, functions, & processes
  - examples
- practical implementation of error classes within our prototype fault injection tool, Hovac
- evaluation of error model
- discussion & future work

Research Gap

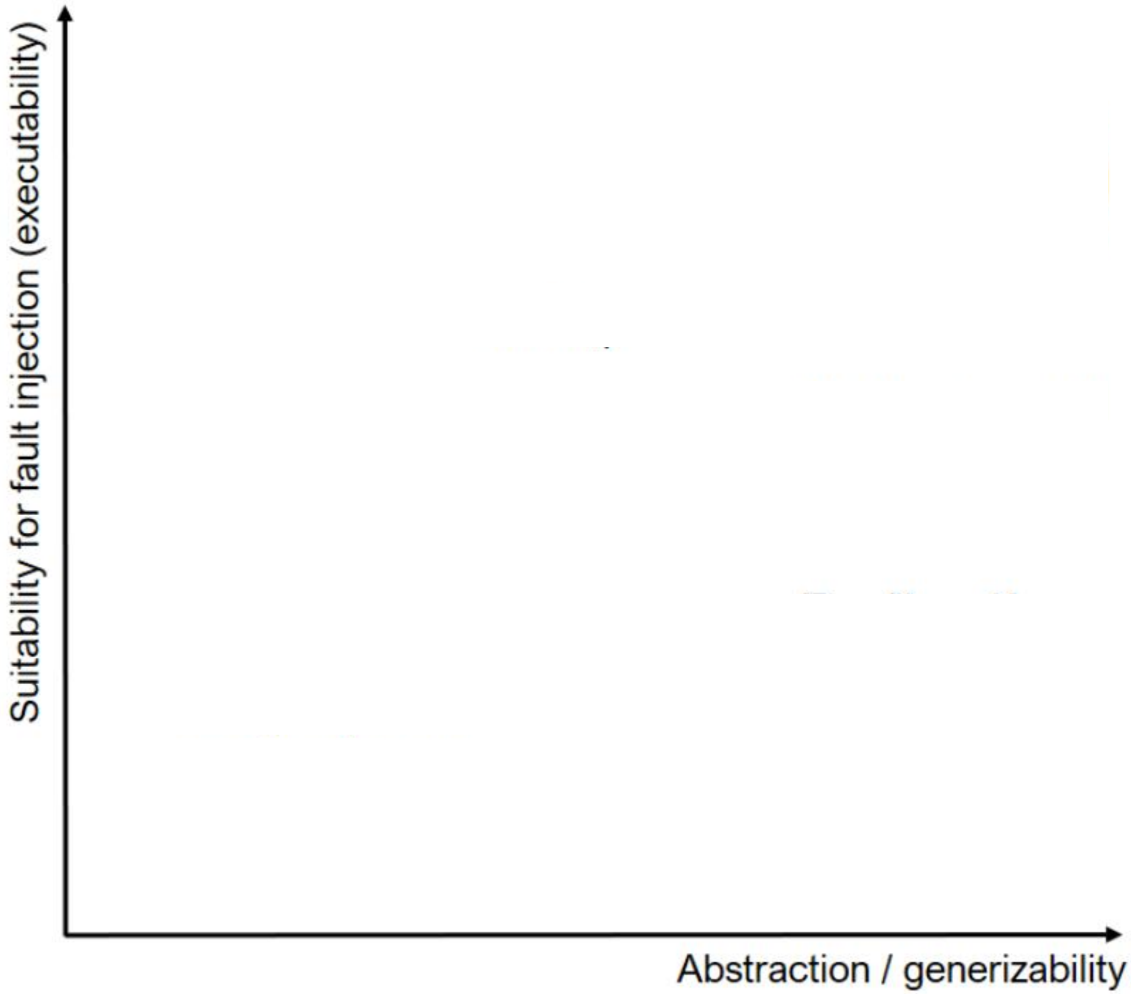
what we are looking for:
error models which are both

- suitable for fault injection (i.e., executable and based on realistic data)
- generalizable

Research Gap

- bug fixes, or generalized patterns of such fixes
  K. Pan, S. Kim, and E. J. Whitehead, Jr., "Toward an understanding of bug fix patterns," *Empirical Softw. Engg.*, vol. 14, no. 3, pp. 286–315, Jun. 2009.
- behavioral models
  T. Kremenek, A. Y. Ng, and D. R. Engler, "A factor graph model for software bug finding." in *IJCAI*, 2007, pp. 2510–2516.
- formal grammar-based fault specifications
  R. A. DeMillo and A. P. Mathur, "A grammar based fault classification scheme and its application to the classification of the errors of tex," Citeseer, Tech. Rep., 1995.
- Common Weakness Enumeration database
  S. Christey, J. Kenderdine, J. Mazella, and B. Miles, "Common weakness enumeration," Mitre Corporation.
- Orthogonal Defect Classification
  R. Chillarege, I. S. Bhandari, J. K. Chaar, M. J. Halliday, D. S. Moebus, B. K. Ray, and M.-Y. Wong, "Orthogonal defect classification-a concept for in-process measurements," *Software Engineering, IEEE Transactions on*, vol. 18, no. 11, pp. 943–956, 1992.

Research Gap



what we are looking for: **error models** which are both

- suitable for fault injection (i.e., executable and based on realistic data)
- generalizable

Error Model

- A system failure is an event that occurs when the delivered service deviates from correct service. A system may fail either because it does not comply with the specification or because the specification did not adequately describe its function.
  A. Avizienis, J.-C. Laprie, B. Randell, and C. Landwehr, "Basic concepts and taxonomy of dependable and secure computing," *Dependable and Secure Computing, IEEE Transactions on*, vol. 1, no. 1, pp. 11–33, 2004.
- **failure cause model** (or "fault model") is complement to program specification
  - what can go wrong?
  - often implicit & not stated explicit
  - aim: explicit error model

Error Model

overview of error classes

- computation
- environment
- timing
- race condition
- memory
- control flow

Error Model

Computation

- variables, in particular computation results of primitive data types, contain a value different from what was expected.
  - Off by One (CWE ID 193)
  - Signed to Unsigned Conversion (CWE ID 195)

Timing

- certain part of the code takes more than the expected time to execute
  - Hovac: call to a library function returns too late

Error Model

Control Flow

- input triggers an incorrect execution path through the application
  - unhandled exceptions

Environment

- interaction between the program and its environment is other than expected; unforeseen states in the execution environment or the operating system; programmer’s assumptions regarding the environment are violated
  - Signal Errors (CWE ID 387)

Error Model

Race Condition

- accesses to shared memory are not properly synchronized
  - switch statements (CWE ID 365)
  - data shared between multiple threads (CWE ID 366)
  - signal handlers (CWE ID 364)

Memory

- state of the memory is corrupted.
  - specifically Hovac/C/C++: corruption or leaking of heap & stack memory due to programming mistakes
  - Heap-/Stack-based Buffer Overflow (CWE IDs 121-122)

Basic Formal Model

- aim: a description, which is
  - generalizable and applicable to diverse software systems
  - works with automated dependability benchmarking and fault injection
- complementary approach to software verification.
  - abstract specifications and invariants which a program must obey to function correctly: success space
  - error states: explore the failure space

Basic Formal Model

- characterization of software error states in an abstract fashion, while using a minimal amount of machine-, language- and hardware architecture-dependent modelling concepts
- basic building blocks:
  - state
  - functions
  - processes
- static (only properties of current state needed)
- state sequences, environment state

Basic Formal Model

- **state** (internal & environment): set R of *resources*
- resource: r = (*ResourceState, Ownership*) $\in R$
- ownership: set of resource owners
  - $p_i \in P$ (processes in system)
- data in memory: $D \subset R$
  - *ResourceState:* $s = <s_j, s_{j+1}, \ldots, s_k>$
    $j >= 0 \wedge k <= m$ (range of addressable memory)
- pre-defined states:
  - *scheduled*($p \in P$); next function call from process *p*
  - *output*($r_1; r_2$); resource state of r_1 is written to r_2

Basic Formal Model

- **functions**: type of events, which transfers input data to output data (= modiefies state):
  $f : I \rightarrow O$ where $I, O \subset R$
  - granularity can be arbitrary
  - error states are assumed to be observable only after events, i.e., at function boundaries

- pre-defined functions:
  - *acquireResource*($(s, O), p \in P$); adds a process to the ownership of a resource: $(s, O) \rightarrow (s, O \cup \{p\})$
  - *releaseResource*($(s, O), p \in P$); removes a process from the ownership of a resource: $(s, O) \rightarrow (s, O - \{p\})$

Basic Formal Model

- **processes**: sequential compositions of functions executed one after another
- multiple processes can run concurrently
  - within a process, functions are strictly ordered
  - assumption: at each time instant only one event occurs.
  - concurrency exists, but behavior is equivalent to a sequential system without hardware parallelism
- set of processes P is fixed

Examples

- usage of first order logics quantifiers combined with Linear Temporal Logic (LTL) predicates
  - LTL is commonly used to denote properties of paths over time, or state sequences in a software system
- allows to express that a boolean fact or condition holds
  - *Next* – in the next state
  - *Eventually/Finally* – in some state in the future,
  - *Globally* – in all future states of the current execution path

Examples

Race Condition

- concurrent accesses to shared memory are not properly synchronized
  - all cases where the outcome can differ depending on the interleaving of two processes
  - here: sharing of one resource between processes

$\exists\, r, out \in R, res \in ResourceState, p_1 \in P, s \in t_r :$

$t_r \models r = (res, \{p_1, p_2\}) \wedge Next\ scheduled(p_1) \Rightarrow$
$\neg Eventually\ output(s, out) \wedge$
$t_r \models r = (res, \{p_1, p_2\}) \wedge Next\ scheduled(p_2) \Rightarrow$
$Eventually\ output(s, out)$

Examples

Memory Leak

- allocated memory that cannot be used because the reference to it has been lost

$$\exists p \in P : t_r \models \mathit{Exists}\ \neg \mathit{Globally}\ (r = (*, \{e\}) \wedge \mathit{Next}\ r = (*, \{p \in P\}) \Rightarrow \mathit{Eventually}\ r = (*, \{e\}))$$

- or -

$$\exists p \in P : t_e \models \mathit{Exists}\ \mathit{acquireResource}(r, p) \Rightarrow \neg \mathit{Eventually}\ \mathit{releaseResource}(r, p)$$

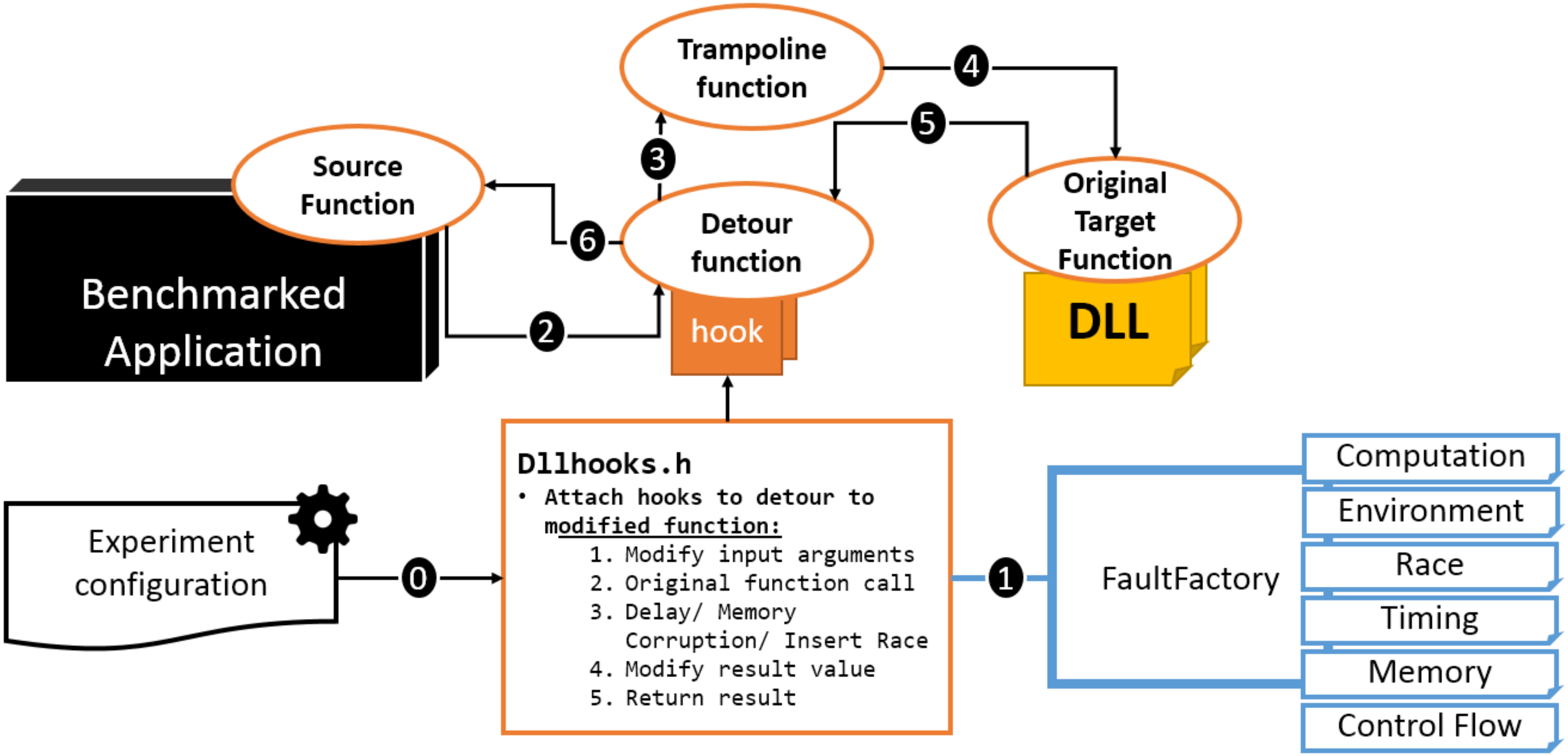
Examples

Buffer overflow

- a memory region, or buffer, is written beyond its boundaries and no bounds checking was performed
- any operation (event) which modifies state according to this pattern constitutes a buffer overflow:
  $(<s_j, s_{j+1}, \ldots, s_k>, \{p\}) \rightarrow$
  $(<s'_j, s'_{j+1}, \ldots, s'_k>, \{p\}), (<s'_{j'}, \ldots, s'_{k'}>, *)$
  $k' > j' > k \vee j' < k' < j$

Implementation

Hovac




```
Dllhooks.h
• Attach hooks to detour to
  modified function:
    1. Modify input arguments
    2. Original function call
    3. Delay/ Memory
       Corruption/ Insert Race
    4. Modify result value
    5. Return result
```

https://github.com/laena/hovac

Implementation

- based both on formal model and on CWE DB
- selected CWE entries (“*weaknesses*”) describe instances of our error classes
- for each error class, different errors – one per CWE entry – are implemented
- “static” errors (only operate on the current state)
  - activation takes place before or after the intercepted function call, function call itself takes place as usual
- “dynamic” errors
  - lambda passed into the activate function is relevant

Implementation

Computation error (static)

- C++ template classes, an instantiation is implemented per type, containing the modification of arguments and return values
  - examples (CWE ID): Weakness Class: Incorrect Calculation (682), Off by One (193), Integer Overflow or Wraparound (190), Incorrect Conversion between Numeric Types (681)

Implementation

- sample code: Off by One computation error type

```
template<typename Type>
class OffByOne : public ComputationError<Type>
{
public:
  OffByOne(std::string cweID = std::string("193")) : ComputationError
        <Type>(cweID) {};

  Any activate(AnyList arguments, LambdaPtr = nullptr) const override
          {
    for (std::reference_wrapper<Type> arg : typeCastArguments(
          arguments))
      arg.get()++;
    return Any();
  };
};
POCO_EXPORT_CLASS(ComputationError<unsigned int>)
```

Implementation

Environment error (static)

- execution environment is shared due to the API hooking approach – it can be manipulated programmatically
  - examples (CWE ID): Signal Error (387), Improper Privilege Management (269), Information Exposure Through Environmental Variables (526)

Implementation

Timing error (dynamic)

- timing of a call to a third-party library is delayed artificially. C++ provides versatile means to do so using its thread support library.
  - examples (CWE ID): Excessive Iteration (834), Loop with Unreachable Exit Condition (835), Uncontrolled Recursion (674)

Implementation

Race condition (dynamic)

- erroneous behavior in a new thread spawned by Havoc - for race conditions dependent on environment state and input data, no race conditions between multiple third-party libraries
  - examples (CWE ID): Weakness Class: Concurrent Execution using Shared Resource with Improper Synchronization (362), Race Condition within a Thread (366), Time-of-check Time-of-use (TOCTOU) Race Condition (367), Context Switching Race Condition (368)

Implementation

Memory error (dynamic)

- manipulate heap and stack memory before or after the detoured function call (e.g. call malloc with an excessive size parameter)
  - examples (CWE ID): Allocation of Resources without Limits (770), Stack-based Buffer Overflow (121-122), Logging of Excessive Data (770), Out-of-bounds Write (787)

Implementation

Control flow error (dynamic)

- exception injection, to test exception handling mechanisms
  - examples (CWE ID): Always-Incorrect Control Flow Implementation (670), Incorrect Behavior Order (696), Incorrect Control Flow Scoping (705)

Implementation

- sample code: exception injection

```
template<typename Type>
class UncaughtException : public ControlFlowError
{
public:
  UncaughtException() : ControlFlowError("248" /* cweID */) {};

  Any activate(AnyList arguments, LambdaPtr lambda) const override {
    std::string what = "uncaught exception";
    throw Type(what.c_str());

    (*lambda)();
  }
};
POCO_EXPORT_CLASS(UncaughtException<std::runtime_error>)
```

Evaluation

- formality:
  - our model is based on formal considerations
  - most error classes can be represented statically (just a snapshot of the running software and not a potentially infinite sequence of states needs to be considered)
- executability:
  - implementation conforming to our C++ AbstractError interface
  - the interface turned out to be versatile and expressive enough for all our needs.
  - our architecture allows for simple development of extension DLLs

Evaluation

- realism
  - based on CWE database, which contains empirical knowledge from real world industrial software systems
  - implementations of errors in the different classes based on a structured search of CWE database.
  - we used “C++” keyword to search, but additional not classified as C or C++-language relevant, also need to be considered

Discussion & Future Work

Hasso Plattner Institut

- error model for fault injection
- based on community knowledge of software problems (CWE database)
- consists of a formalization of concepts needed for describing error states in a running system…
- …as well as an implementation thereof

Discussion & Future Work

- further evaluation & extension of our error model
- provide an automated deduction of error implementations from bugs
- model excludes probability and frequency over time of error states
- integrate profiling and field failure data
- error model is limited to the application layer of a single, potentially multithreaded compute node
- extend error model to cloud software systems
  - distributed nature,
    complexity of virtualized software stack

Summary

- fault tolerance of complex software systems can be assessed experimentally using fault injection
- to become an effective & systematic testing strategy: requires a realistic and well-defined failure cause model
- failure cause models are frequently incomplete, informal, and implicit or application-dependent

Summary

- we present a formal error model tailored for multi-threaded single-node applications
- we provide a formal error model based on Common Weakness Enumeration (CWE) database of real world software problems to derive classes of error states
  - static (i.e., detectable from a snapshot of the system)
  - dynamic (i.e., dependent on history of previous states).
- we show how to implement our error model so that it becomes executable in our fault injection tool, Hovac ***https://github.com/laena/hovac***