State machine modelling and property based testing combined with fault injection

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Motivation

- Fault tolerant (distributed) systems, hard to get right (many edge cases)
- *Simple Testing Can Prevent Most Critical Failures* paper (Yuan et al. 2014)
  - The authors studied 198 randomly sampled user-reported failures from five distributed systems (Cassandra, HBase, HDFS, MapReduce, Redis)
  - "Almost all catastrophic failures (48 in total – 92%) are the result of incorrect handling of non-fatal errors explicitly signalled in software."
  - Example: `... } catch (Exception e) { LOG.error(e); // TODO: we should retry here! }`

Overview

- Property based testing (pure/side-effect free/stateless programs)
- State machine modelling (monadic/has side-effect/stateful programs)
- Fault injection (provoking exceptions)
- Examples using
  - `quickcheck-state-machine` Haskell library for property based testing
  - The principles are general and tool independent

Recap: property based testing

- Unit tests

```haskell
test :: Bool
test = reverse (reverse [1,2,3]) == [1,2,3]
```

- Property based tests

```haskell
prop :: [Int] -> Bool
prop xs = reverse (reverse xs) == xs
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  $\forall xs(\text{reverse}(\text{reverse}(xs)) = xs)$

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- Type theory

```
proof : forall xs -> reverse (reverse xs) == xs
```

State machine modelling (somewhat simplified)

- Datatype of actions/commands that users can perform
- A simplified model of the system
- A transition function explaining how the model evolves for each action
- Semantics function that executes the action against the real system
- Post-condition that asserts that the result of execution matches the model

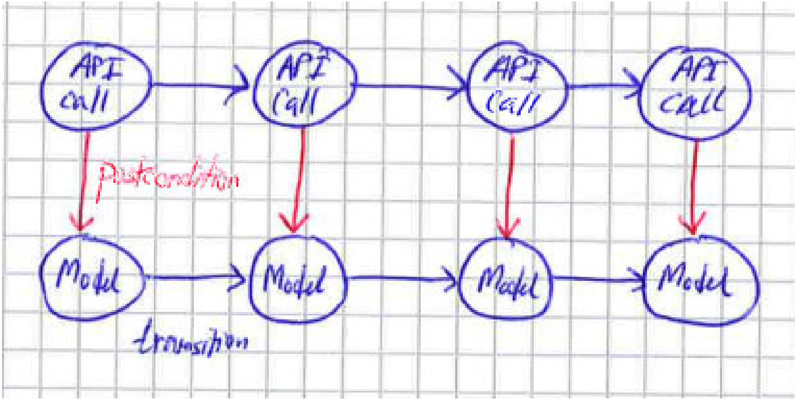
Example: CRUD application

```haskell
data Action = Create | Read | Update String | Delete

type Model = Maybe String

transition :: Model -> Action -> Model
transition _m Create     = Just ""
transition  m Read       = m
transition _m (Update s) = Just s
transition _m Delete     = Nothing
```

Example: CRUD application (continued)

```haskell
data Response = Unit () | String String

semantics :: Action -> IO Response
semantics Create       = Unit   <$> httpReq POST   url
semantics Read         = String <$> httpReq GET    url
semantics (Update s) = Unit   <$> httpReq PUT    url s
semantics Delete       = Unit   <$> httpReq DELETE url

postcondition :: Model -> Action -> Response -> Bool
postcondition (Just m) Read (String s) = s == m
postcondition _m       _act _resp      = True
```

State machine modelling as a picture



Fault injection

- Many different tools and libraries, none native to Haskell
- We'll use the C library `libfiu` (**f**ault **i**njection in **u**serspace)
- Two modes of operation
  - Inject POSIX API/syscall failures
  - Inject failures at user specified failpoints

Fault injection: syscall failures

- Using `fiu-run` directly:

```
fiu-run -x -c 'enable name=posix/io/*' ls
```

- Via `fiu-ctrl` in a possibly different process:

```
fiu-run -x top

fiu-ctrl -c "enable  name=posix/io/oc/open" \
    $(pidof top)
fiu-ctrl -c "disable name=posix/io/oc/open" \
    $(pidof top)
```

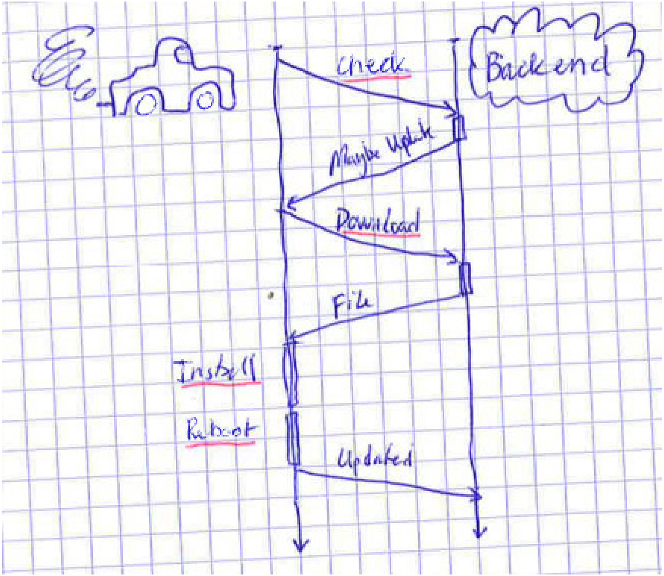
Fault injection: user specified failpoints

```
size_t free_space() {
        fiu_return_on("no_free_space", 0);

        [code to find out how much free space there is]
        return space;
}

bool file_fits(FILE *fd) {
        if (free_space() < file_size(fd)) {
                return false;
        }
        return true;
}

fiu_init();
fiu_enable("no_free_space", 1, NULL, 0);
assert(file_fits("tmpfile") == false);
```

Examples

- Over-the-air updates of cars (my workplace)
- Adjoint's libraft
- IOHK's blockchain database

Over-the-air updates (picture)



Over-the-air updates

```haskell
data Action = Check | Download | Install | Reboot
            | Inject Fault | DisableFaultInject

data Fault = Network | Kill | GCIOPause | ProcessPrio
           | ReorderReq | SkewClock | RmFile | DamageFile
           | Libfiu (Either Syscall Failpoint)

inject :: Fault -> IO ()  -- Pseudo code
inject Network     = call "iptables -j DROP $IP"
inject Kill        = call "kill -9 $PID"
inject GCIOPause   = call "killall -s STOP $PID"
inject ProcessPrio = call "renice -p $PID"
inject ReorderReq  = call "someproxy" -- Which?
inject SkewClock   = call "faketime $SKEW"
inject RmFile      = call "rm -f $FILE"
inject DamageFile  = call "echo 0 > $FILE"
inject Libfiu      = call "fiu-ctrl -c $FAULT $PID"
```

Over-the-air updates (continued)

```haskell
data Model = Model { fault :: Maybe Fault, ... }

transition :: Model -> Action -> Model
transition m (Fault f)           = m { fault = Just f }
transition m DisableFaultInject = m { fault = Nothing }
transition m ...

postcondition :: Model -> Action -> Response -> Bool
postcondition m act resp = case (fault m, act) of
  (Nothing,      Download) -> resp == Ok
  (Just Network, Download)
      -> resp == TimeoutError
  (Just (Libfiu (Right InstallFailure)), Install)
      -> resp == FailedToInstallError
  ...
```

Over-the-air updates (continued 2)

```
prop_reliable :: Property
prop_reliable = forAllActions $ \acts -> do
  (device, update) <- setup
  schedule update device
  let model = initModel { device = Just device }
  (model', result) <- runActions acts model
  assert (result == Success) -- Post-conditions hold
  runActions [ DisableFaultInject
             , Check, Download, Install, Reboot ]
             model'
  update' <- currentUpdate device
  assert (update' == update) -- Always able to recover
```

Adjoint's `libraft`

- Adjoint's libraft
  - Simplified think of it as distributed and fault-tolerant "CRUD applicaiton example"
  - Injected faults: killing nodes and network traffic loss

IOHK's blockchain database

- IOHK's blockchain database
  - File system mock tested against real file system
  - Database tests built on top of file system mock
  - Fault are injected into the file system mock

Further work

- Fault injection library for Haskell, c.f.:
  - FreeBSD's failpoints
  - Rust's `fail-rs` crate
  - Go's `gofail` library
- Jepsen-like tests: parallel state machine testing with fault injection and linearisability
- Lineage-driven fault injection (Alvaro, Rosen, and Hellerstein 2015)

Conclusion

- Fault injection can help causes exceptional circumstances
- Exceptional circumstances are by definition rare and hence less likely to be tested
- Exceptional circumstances are often edge cases and hence less likely to be considered when writing the program
- Exceptional circumstances will nevertheless occur in any long running system
- By combining fault injection with property based testing we force ourselves to consider these exceptional cases

References

Alvaro, Peter, Joshua Rosen, and Joseph M. Hellerstein. 2015. "Lineage-Driven Fault Injection." In *Proceedings of the 2015 ACM SIGMOD International Conference on Management of Data*, 331–46. SIGMOD '15. New York, NY, USA: ACM. doi:10.1145/2723372.2723711.

Yuan, Ding, Yu Luo, Xin Zhuang, Renna Guilherme, Xu Rodrigues, Yongle Zhao, Pranay U Zhang, Michael Jain, and Michael Stumm. 2014. "Simple Testing Can Prevent Most Critical Failures — An Analysis of Production Failures in Distributed Data-Intensive Systems," October. doi:10.13140/2.1.2044.2889.