Comprehensive and Efficient Runtime Checking in System Software through Watchdogs

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HOTOS XVII

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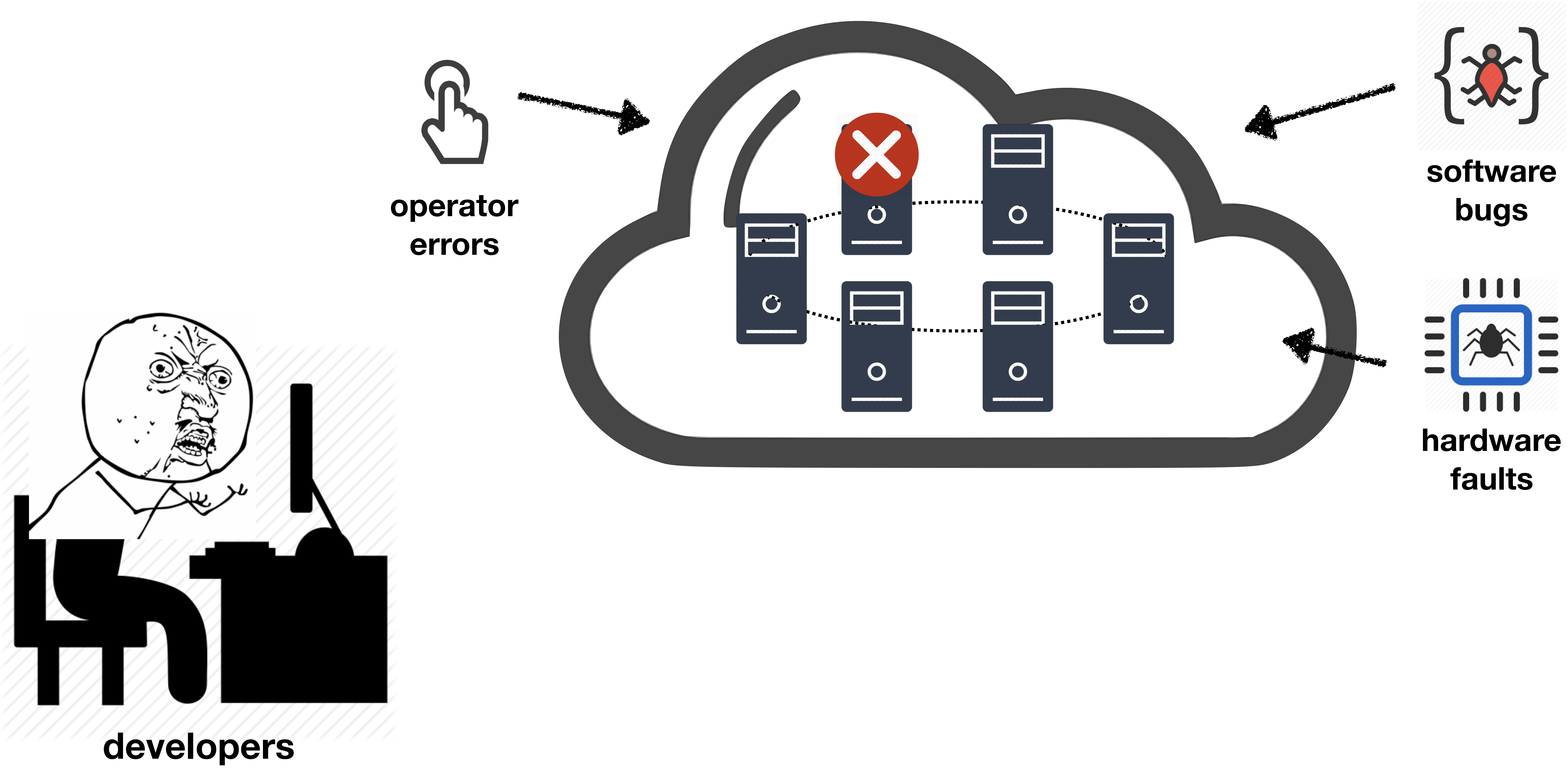
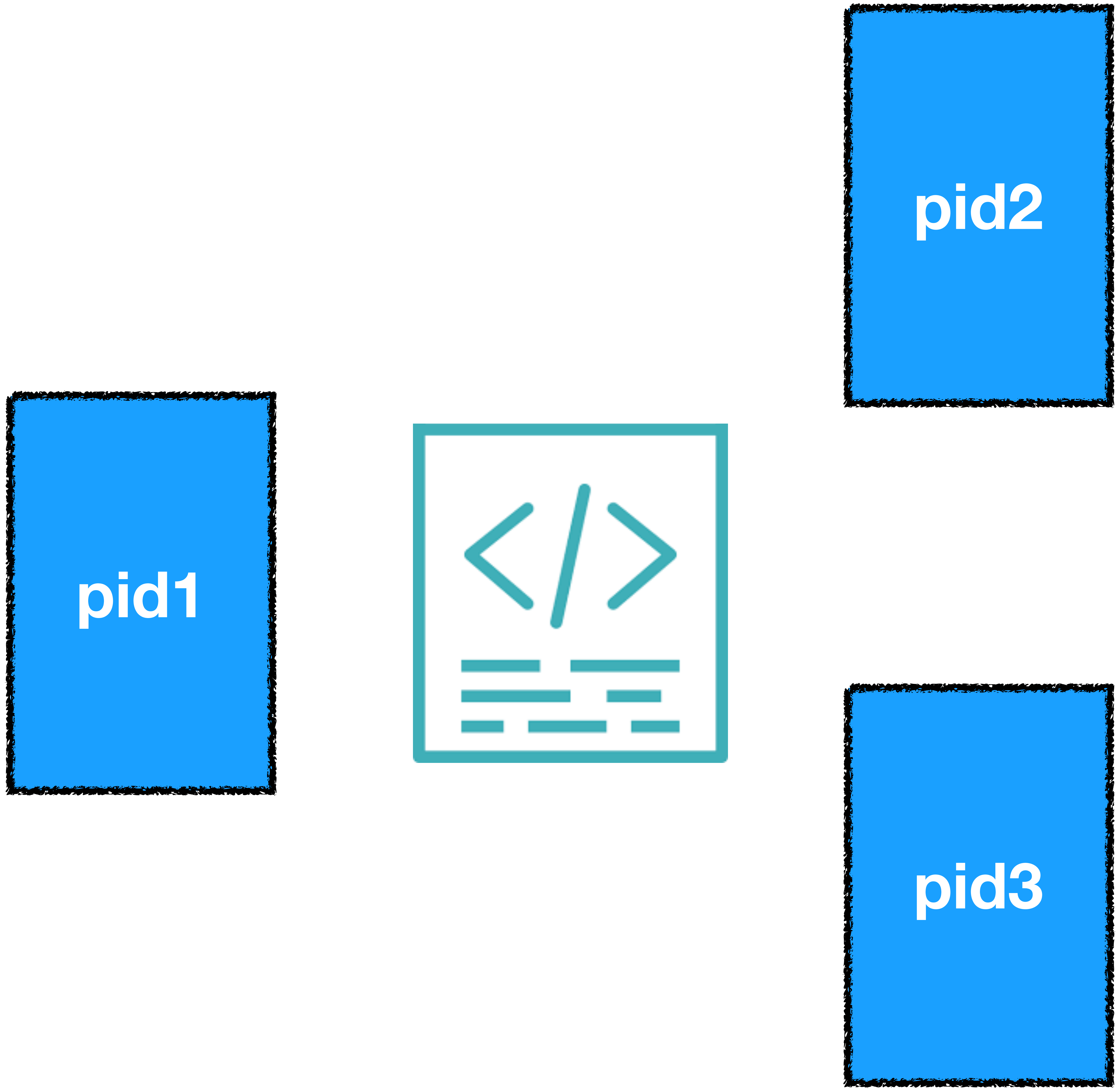
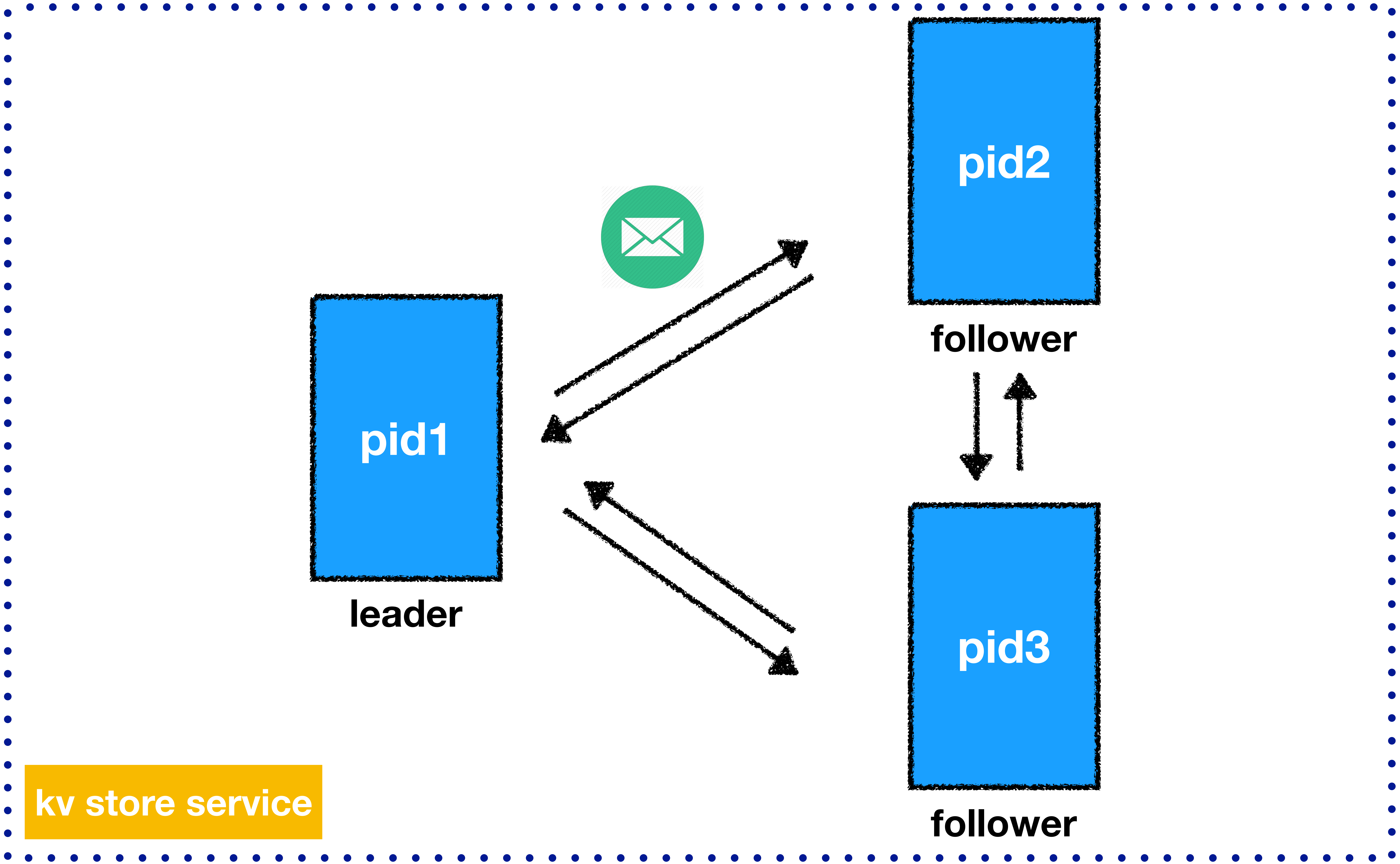
All large systems inevitably fail



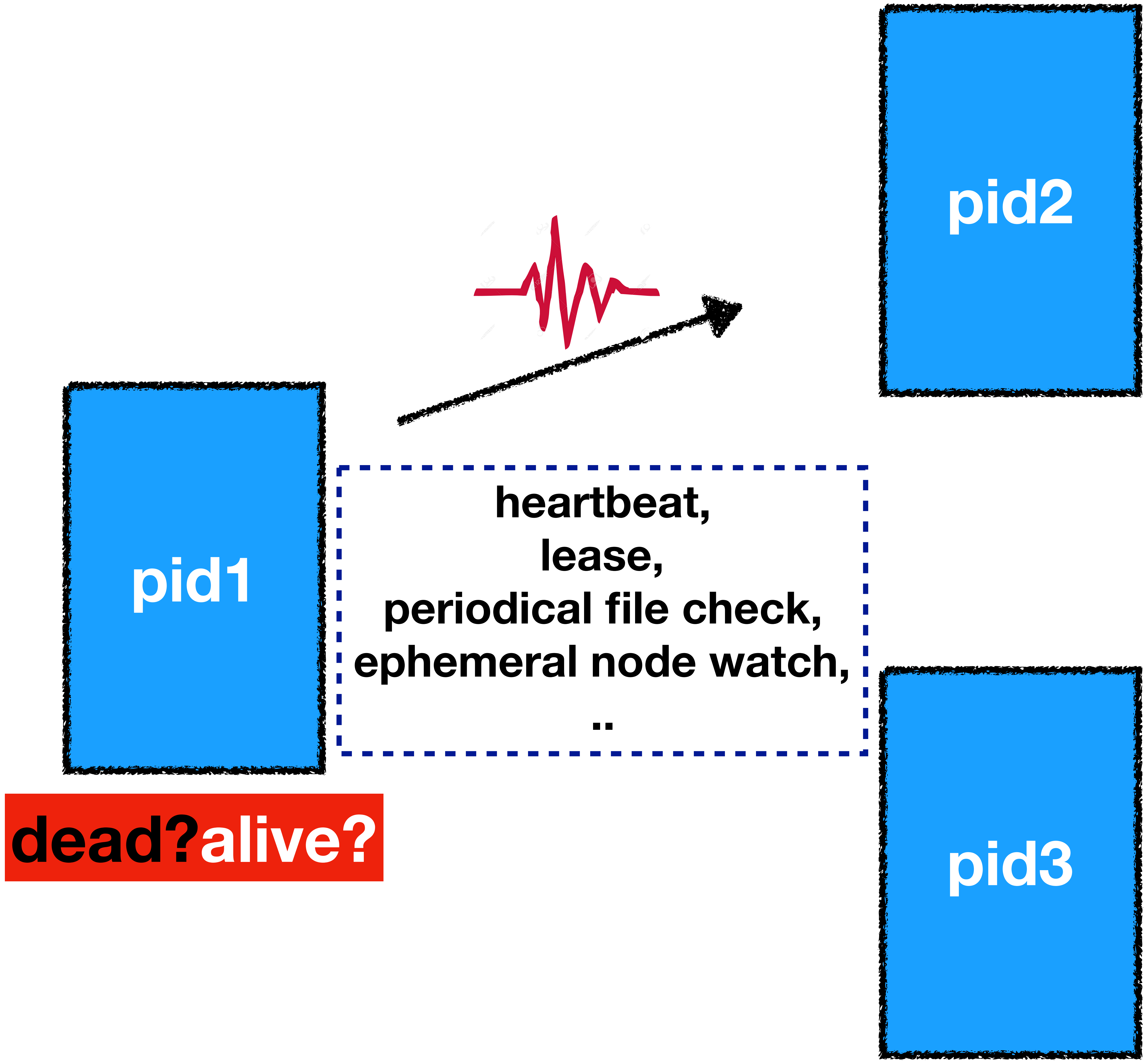
Process-level failure detector abstraction



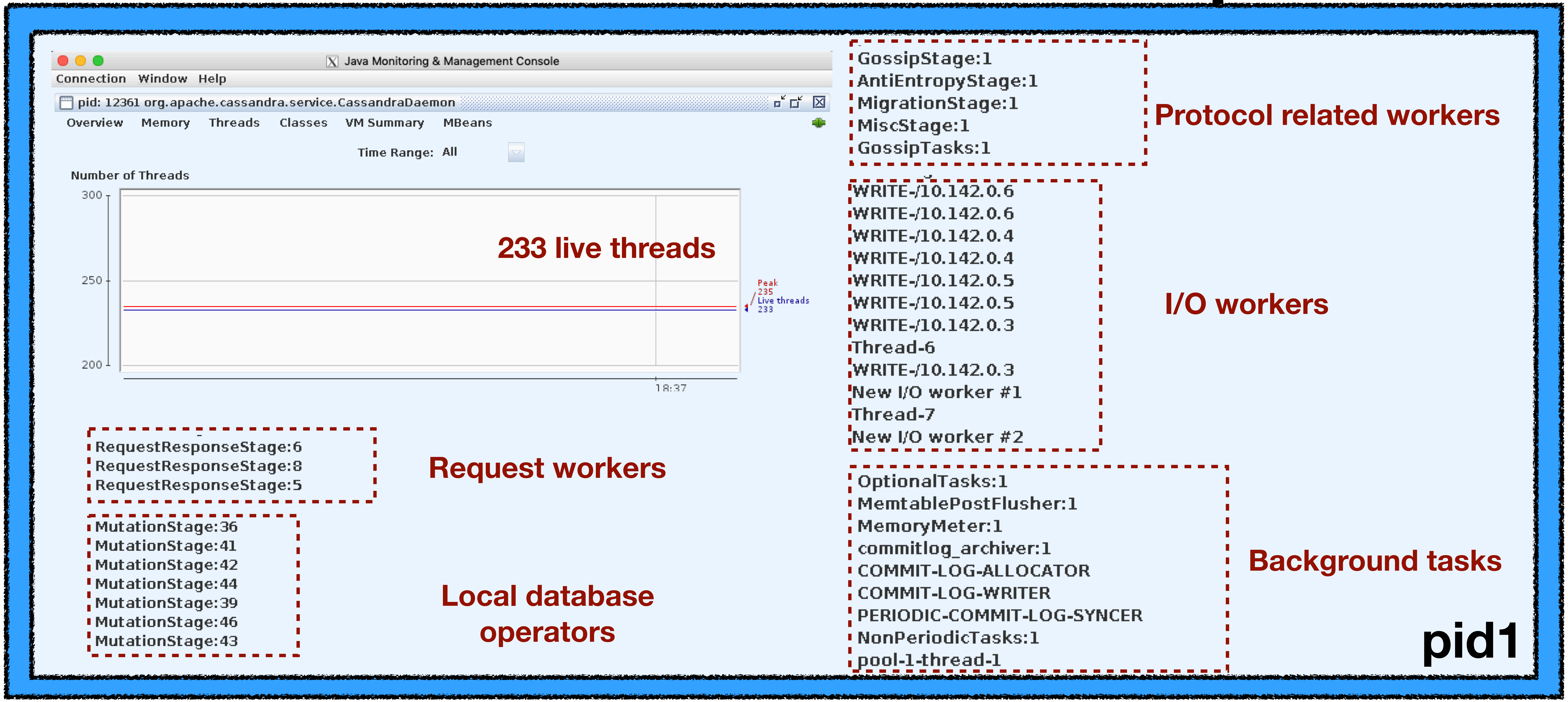
Process-level failure detector abstraction



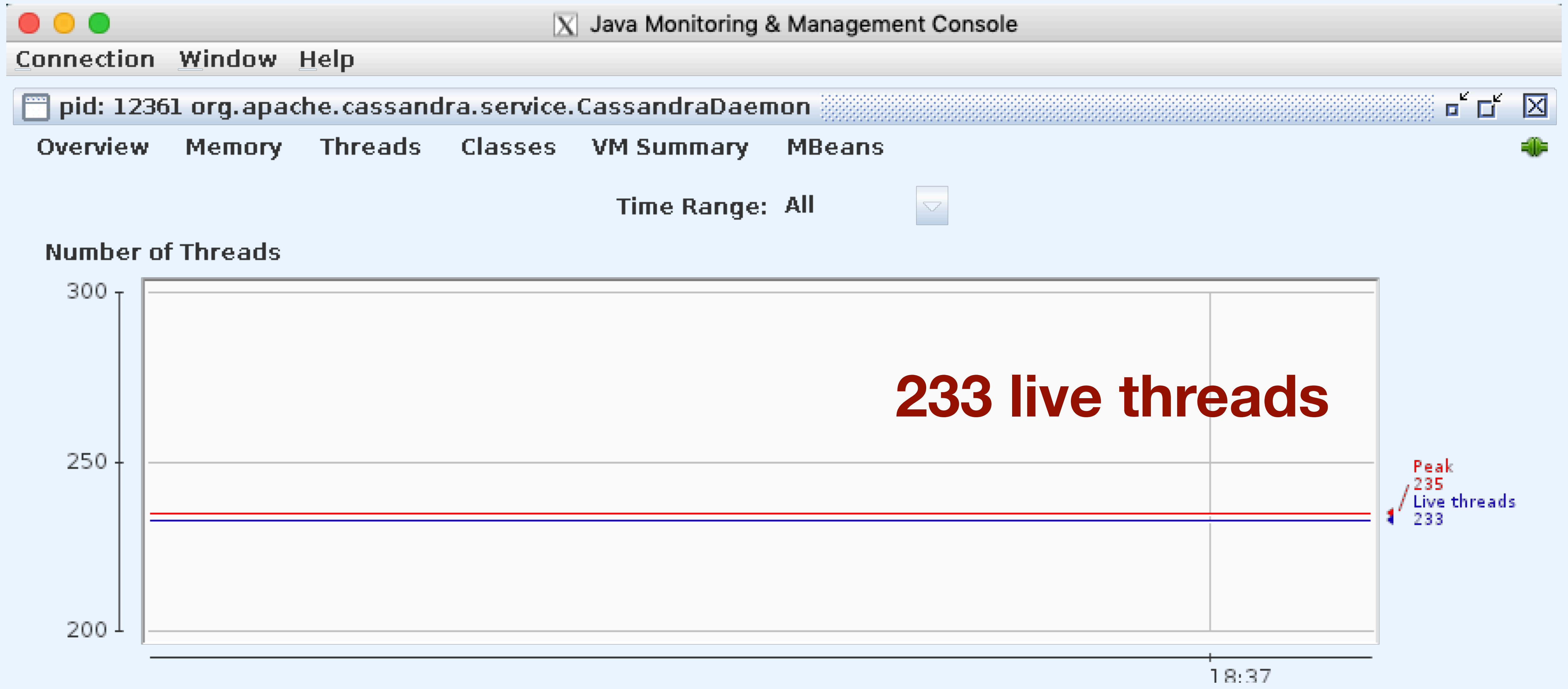
Process-level failure detector abstraction



Modern software is complex



Modern software is complex



GossipStage:1
AntiEntropyStage:1
MigrationStage:1
MiscStage:1
GossipTasks:1

Protocol related workers

WRITE-/10.142.0.6
WRITE-/10.142.0.6
WRITE-/10.142.0.4
WRITE-/10.142.0.4
WRITE-/10.142.0.5
WRITE-/10.142.0.5
WRITE-/10.142.0.3
Thread-6
WRITE-/10.142.0.3
New I/O worker #1
Thread-7
New I/O worker #2

I/O workers

RequestResponseStage:6
RequestResponseStage:8
RequestResponseStage:5

Request workers

MutationStage:36
MutationStage:41
MutationStage:42
MutationStage:44
MutationStage:39
MutationStage:46
MutationStage:43

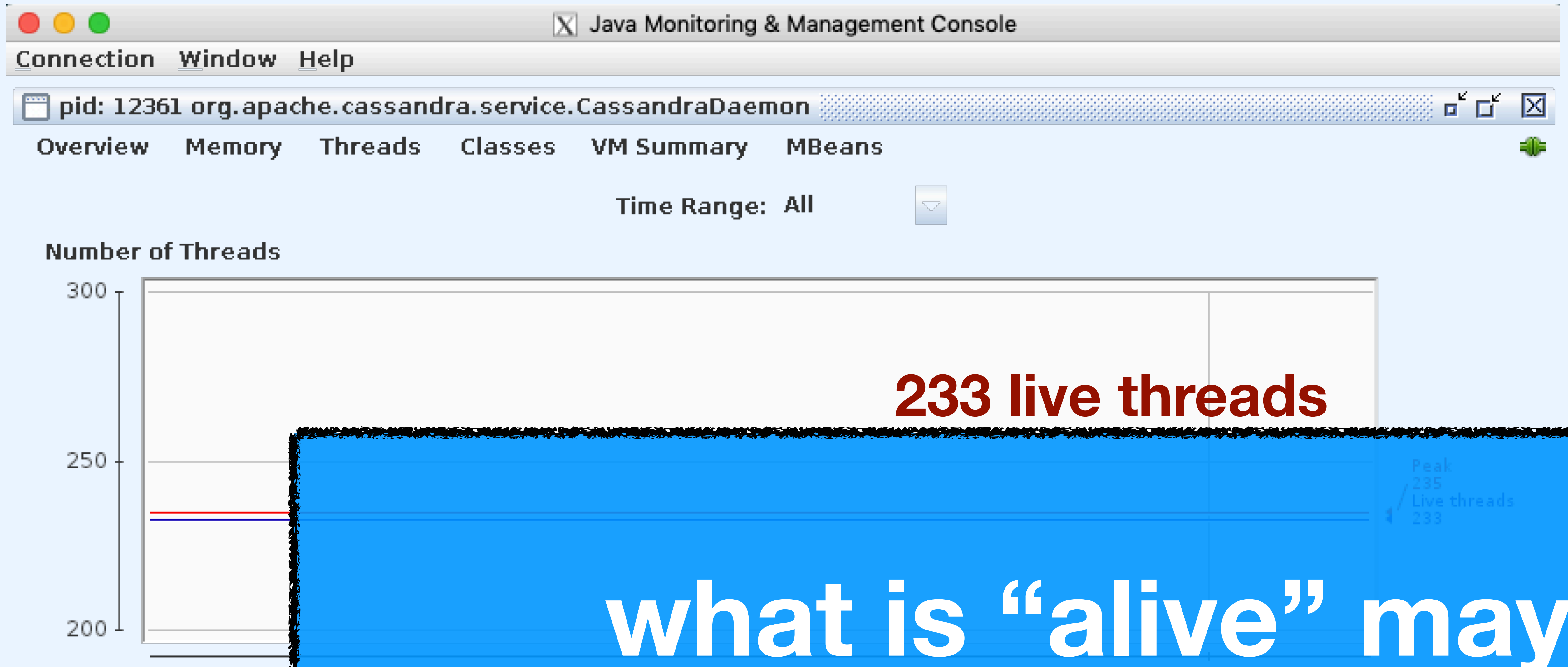
Local database operators

OptionalTasks:1
MemtablePostFlusher:1
MemoryMeter:1
commitlog_archiver:1
COMMIT-LOG-ALLOCATOR
COMMIT-LOG-WRITER
PERIODIC-COMMIT-LOG-SYNCER
NonPeriodicTasks:1
pool-1-thread-1

Background tasks

pid1

Modern software is complex



233 live threads

GossipStage:1
AntiEntropyStage:1
MigrationStage:1
MiscStage:1
GossipTasks:1

Protocol related workers

WRITE-/10.142.0.6
WRITE-/10.142.0.6
WRITE-/10.142.0.4
WRITE-/10.142.0.4
WRITE-/10.142.0.5
WRITE-/10.142.0.5
WRITE-/10.142.0.3
Thread-6
New I/O worker #1
Thread-7
New I/O worker #2

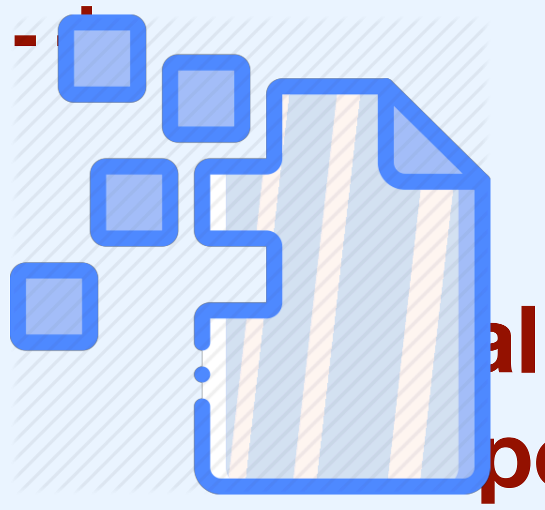
I/O workers

what is "alive" may no longer live

RequestRes
RequestResponseStage:8
RequestResponseStage:5

Request workers

MutationStage:36
MutationStage:41
MutationStage:42
MutationStage:44
MutationStage:39
MutationStage:46
MutationStage:43



al database
perators

OptionalTasks:1
MemtablePostFlusher:1
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commitlog_archiver:1
COMMIT-LOG-ALLOCATOR
COMMIT-LOG-WRITER
PERIODIC-COMMIT-LOG-SYNCER
NonPeriodicTasks:1
pool-1-thread-1

ckground tasks

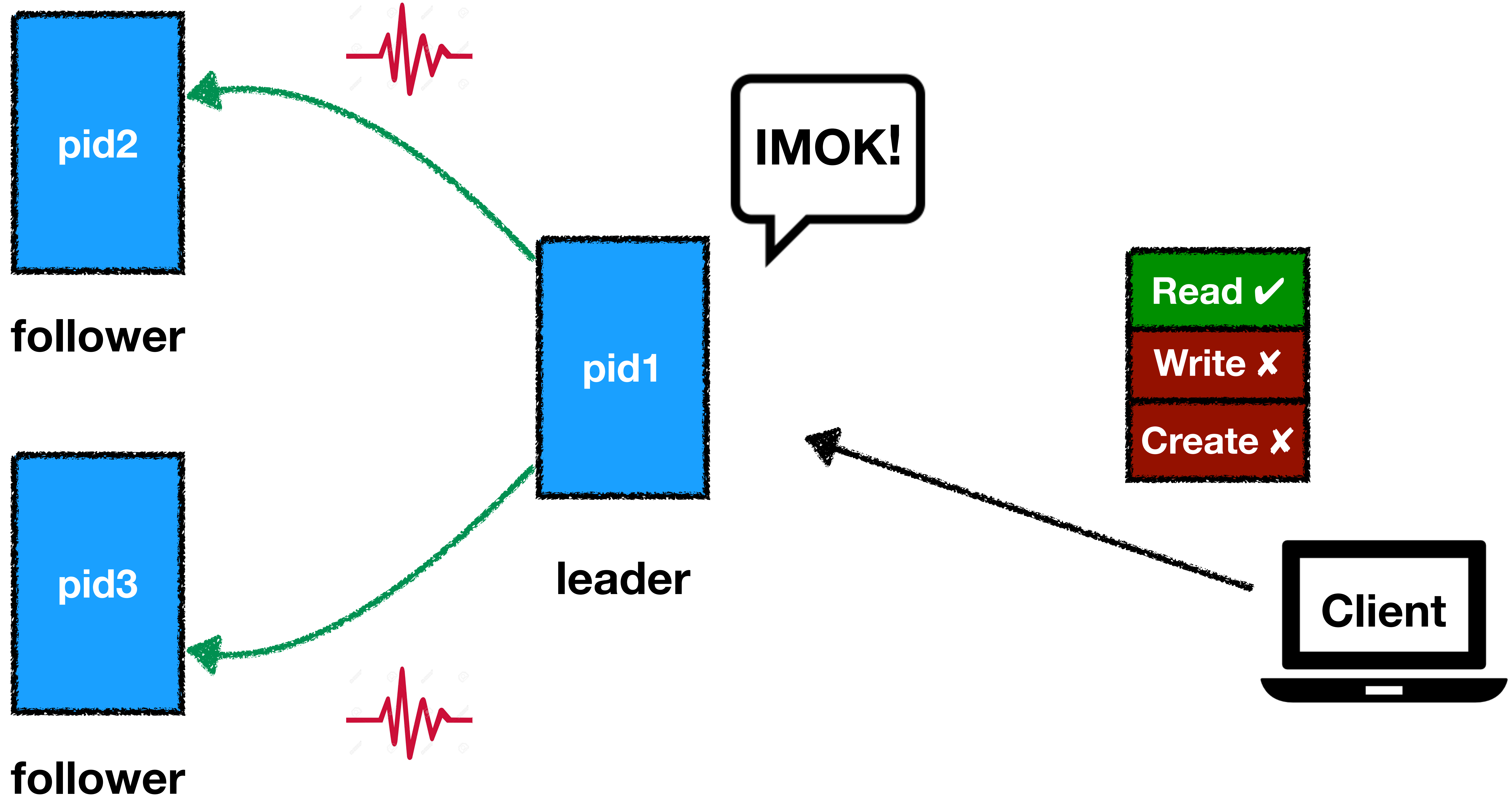
pid1

Real world outages caused by partial failures

Outline

- Motivation
- **Intrinsic software watchdog abstraction**
  - hardware & software watchdogs
  - characteristics
  - checker approach
- **AutoWatchdog: a tool to generate watchdogs**
  - technique: program reduction
- **Challenges & Opportunities**

Why existing failure detectors cannot detect partial failures?



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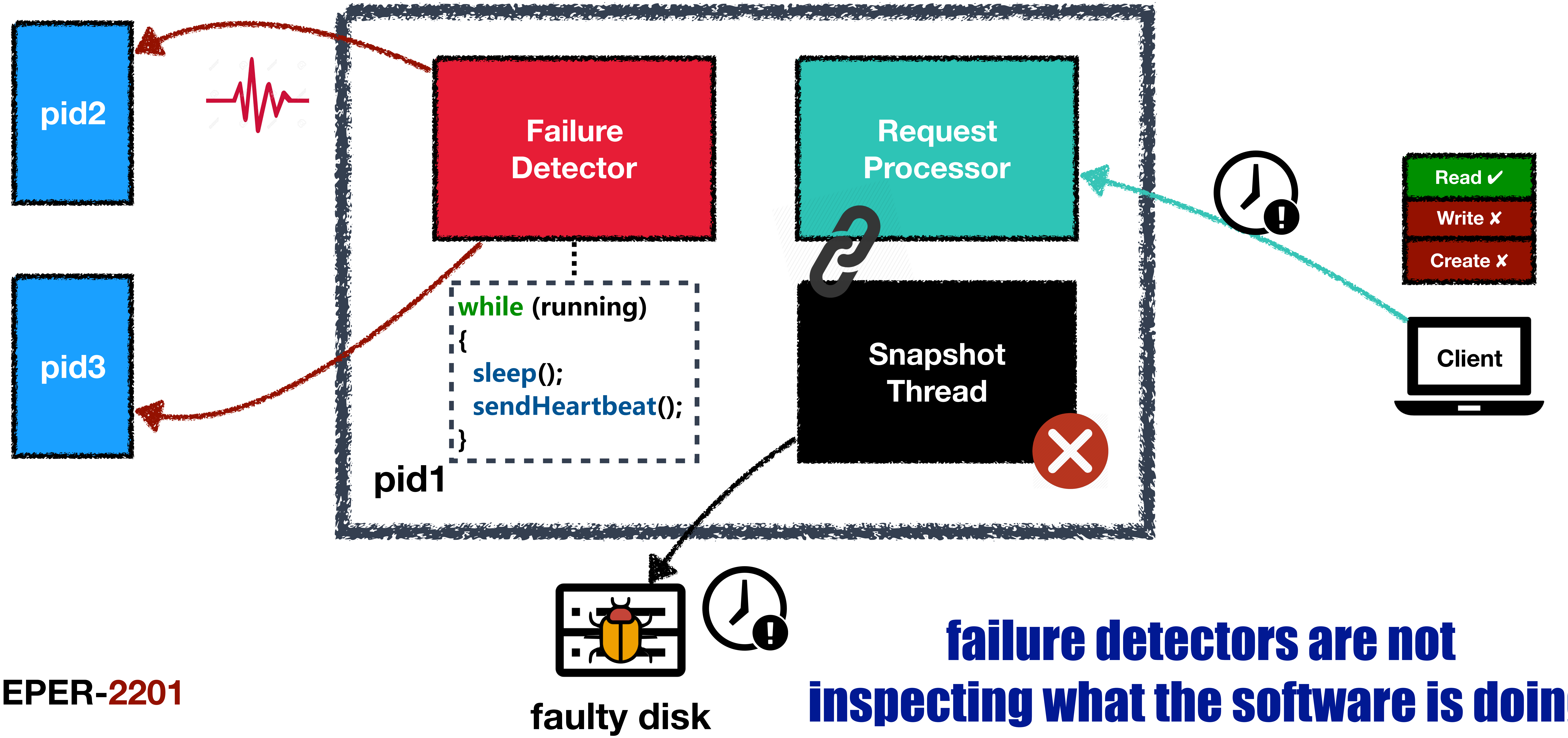
Why existing failure detectors cannot detect partial failures?



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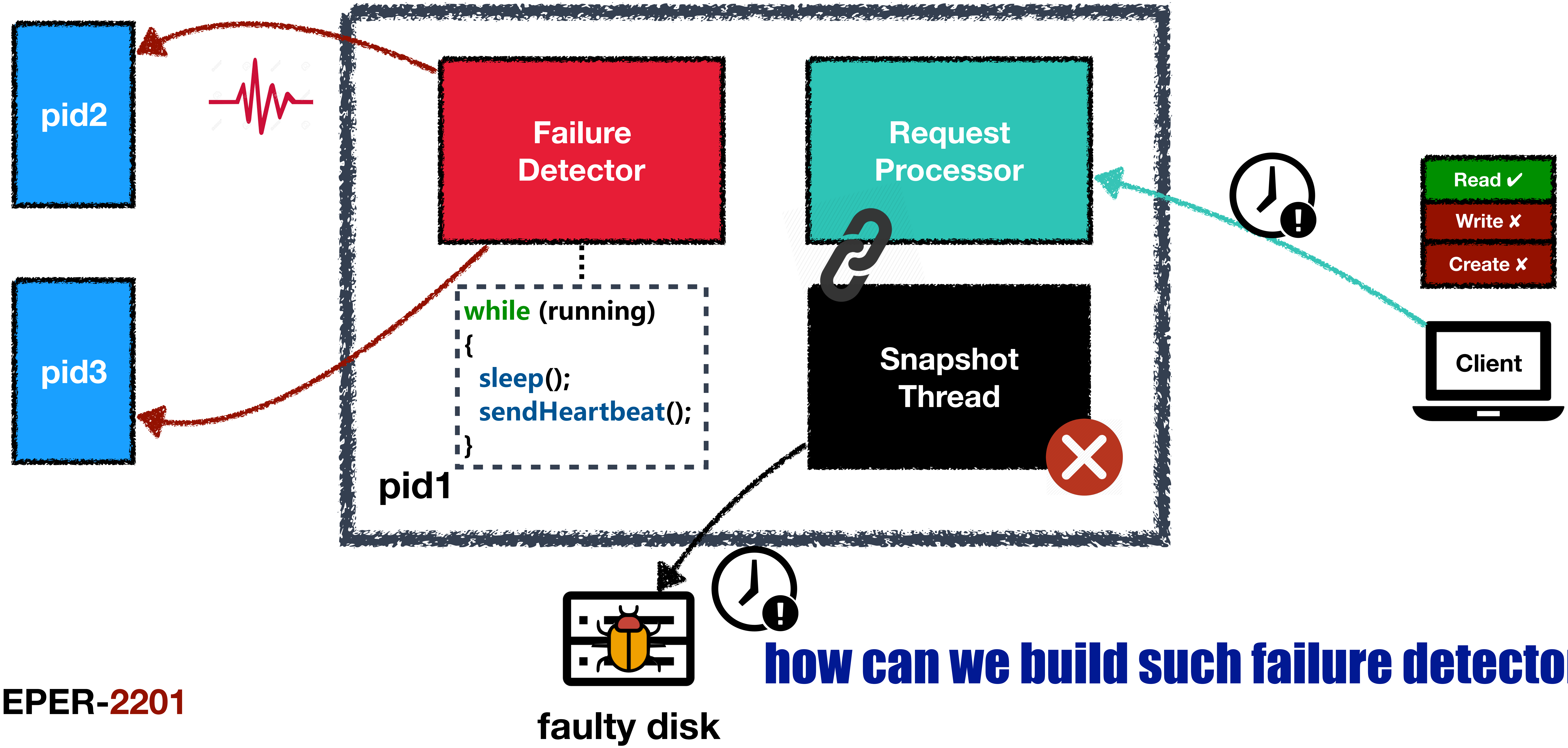
failure detectors are not inspecting what the software is doing

Lesson: failure detectors must comprehensively reflect the process internal status



how can we build such failure detector?

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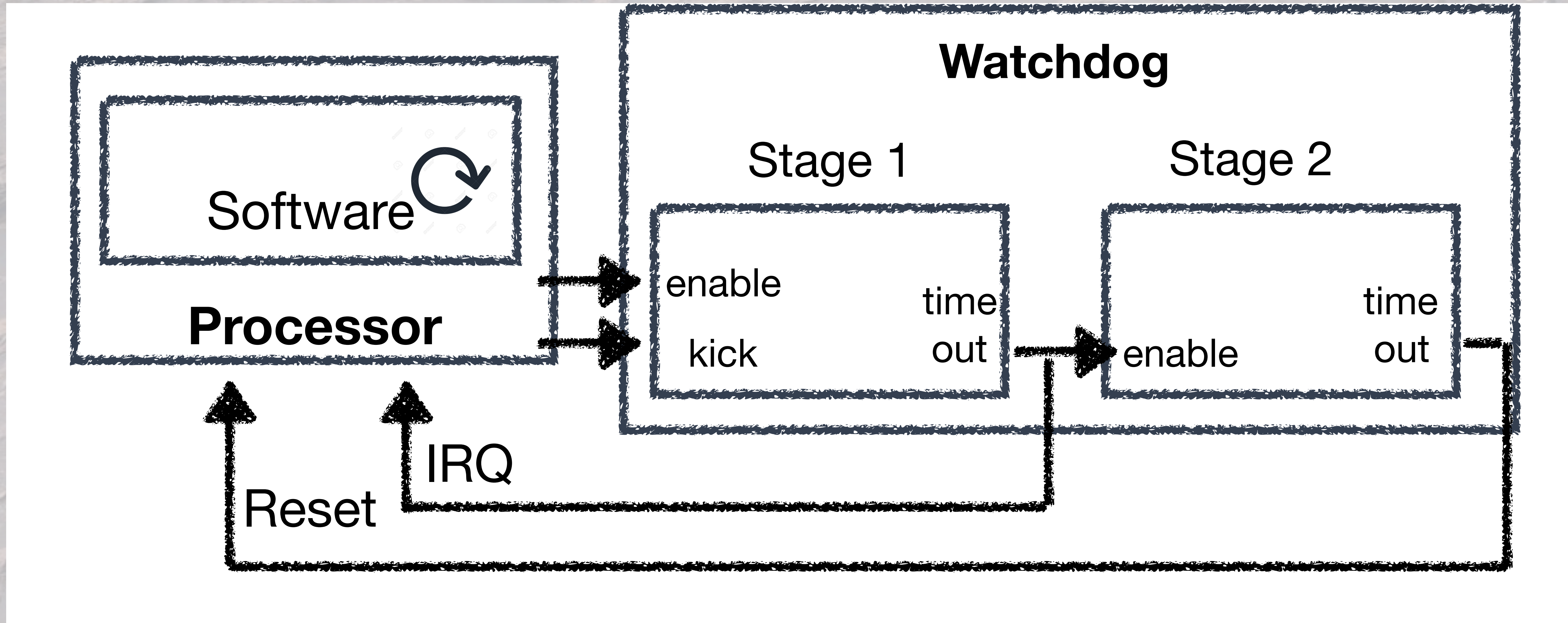
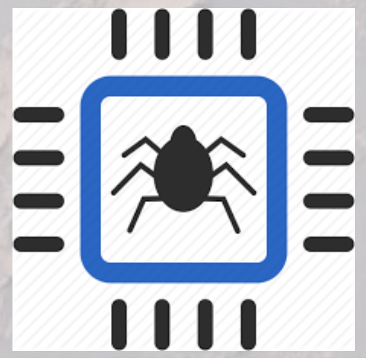
Wisdom from embedded system: Watchdog



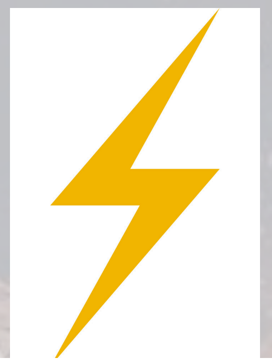
sanity checks

stack depth
status of some mechanical component
deadlock
…



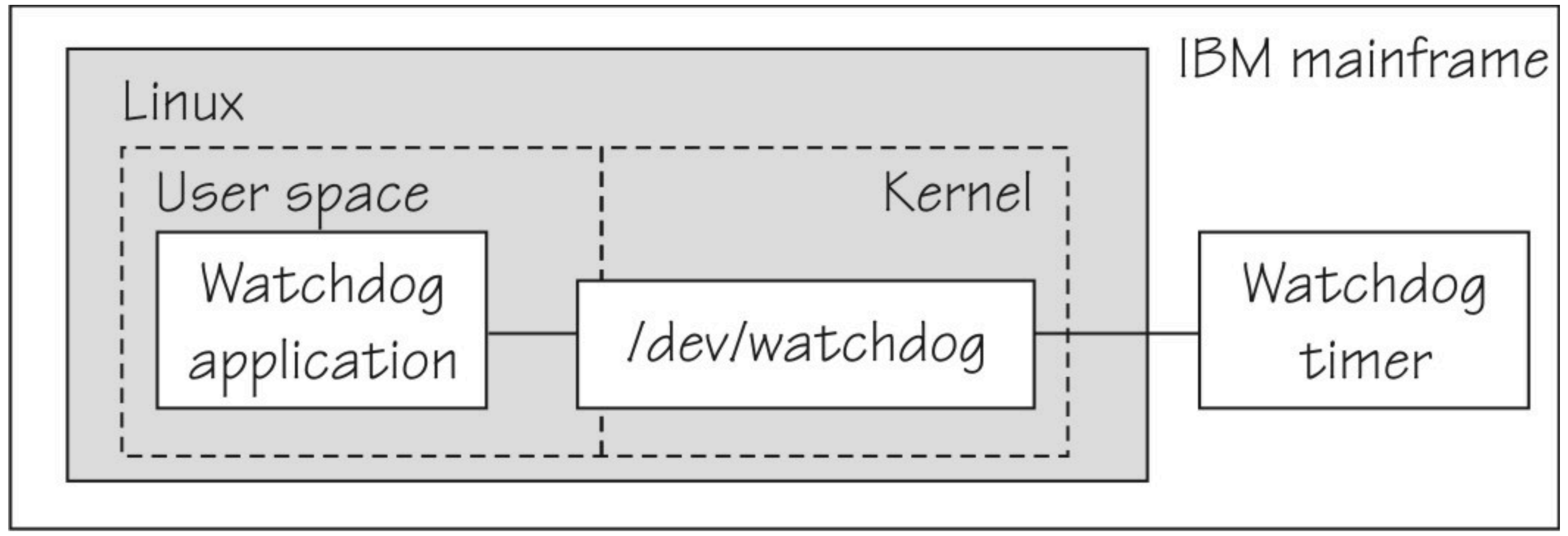
hardware
mechanical component issues
…

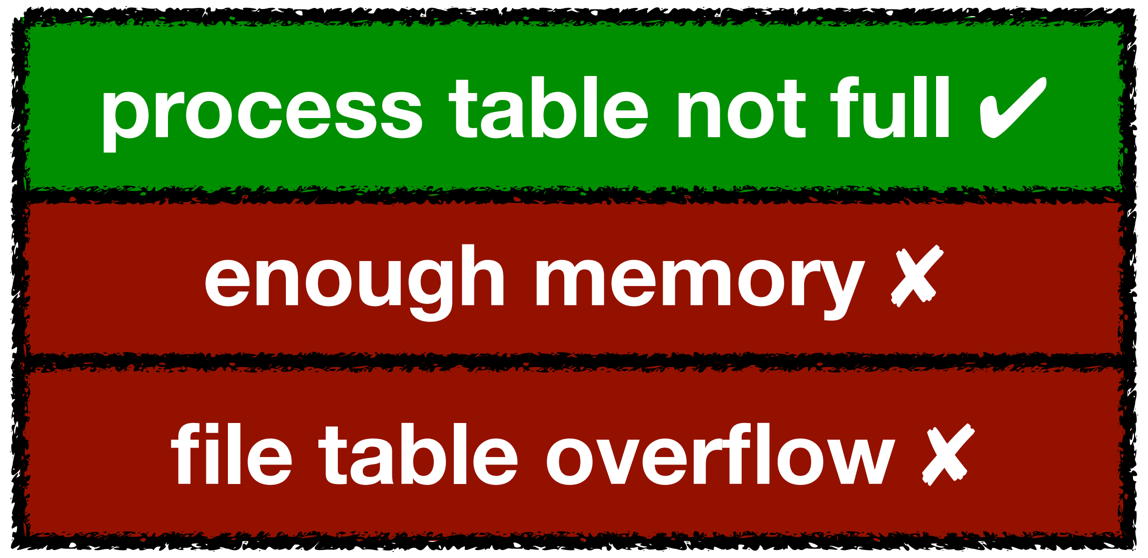
software
infinite loop, accidental jump, deadlock…



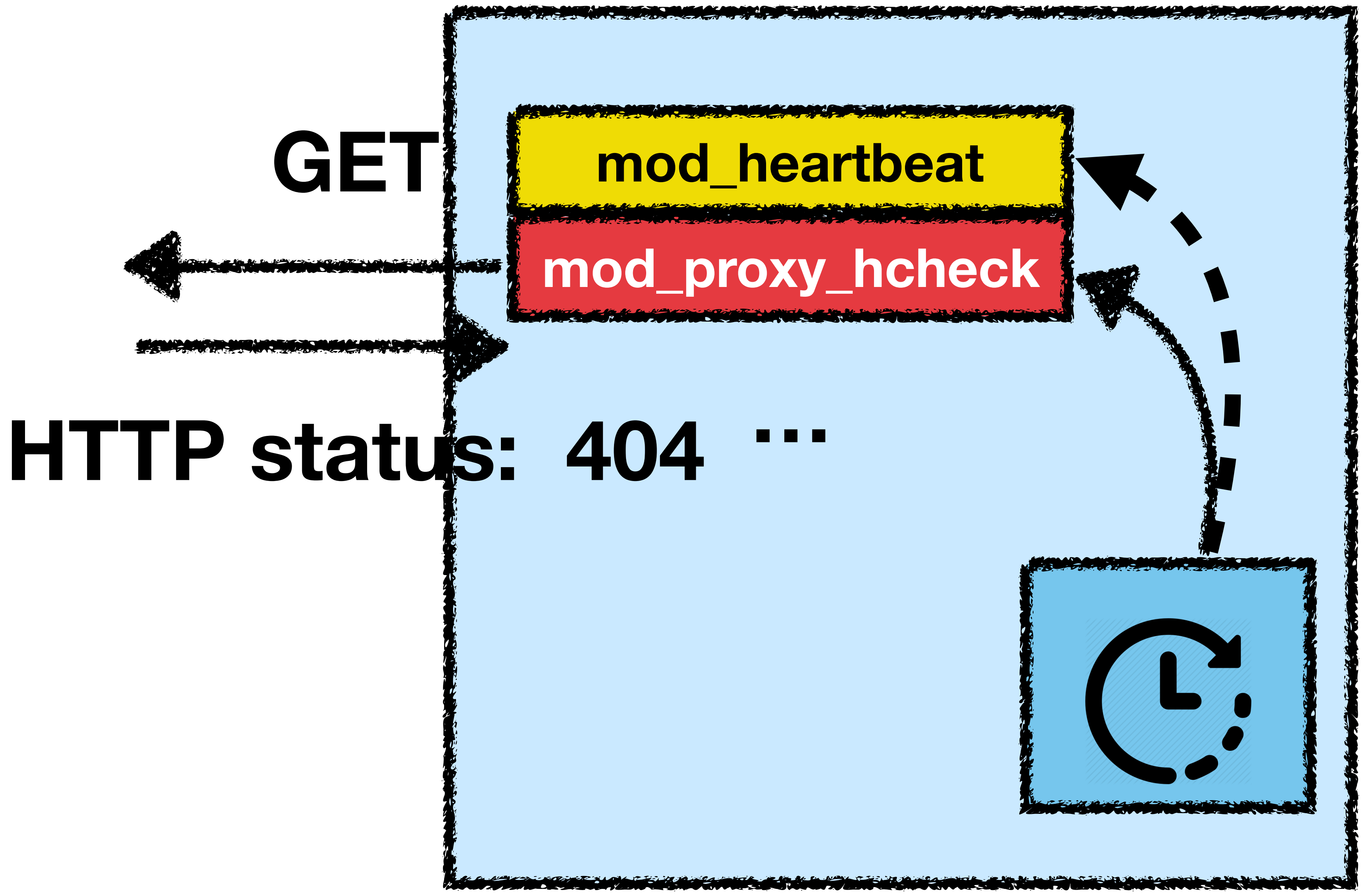
environment
bit flip due to cosmic ray
…

Current software watchdogs are shallow





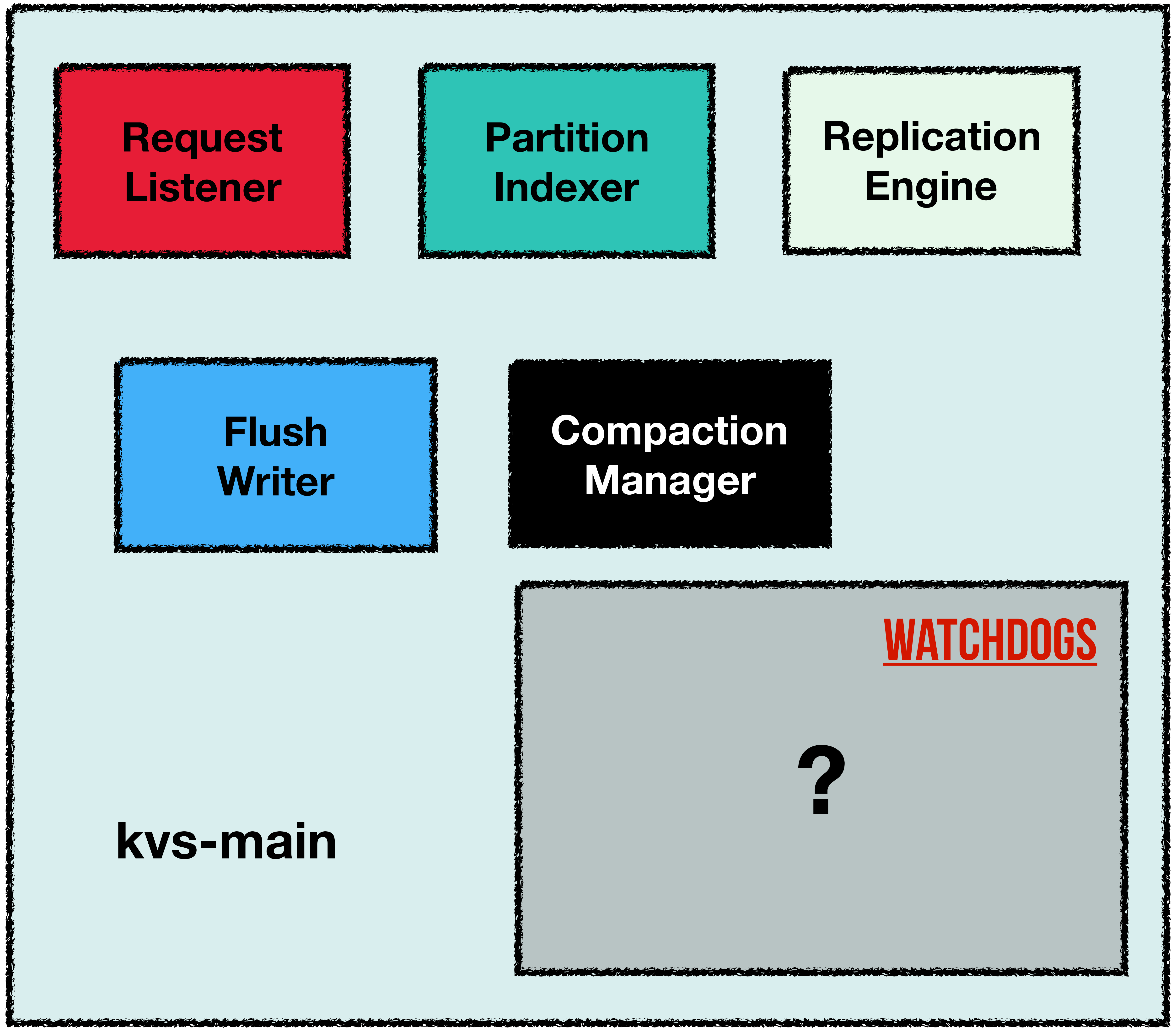
linux watchdog



httpd mod_watchdog

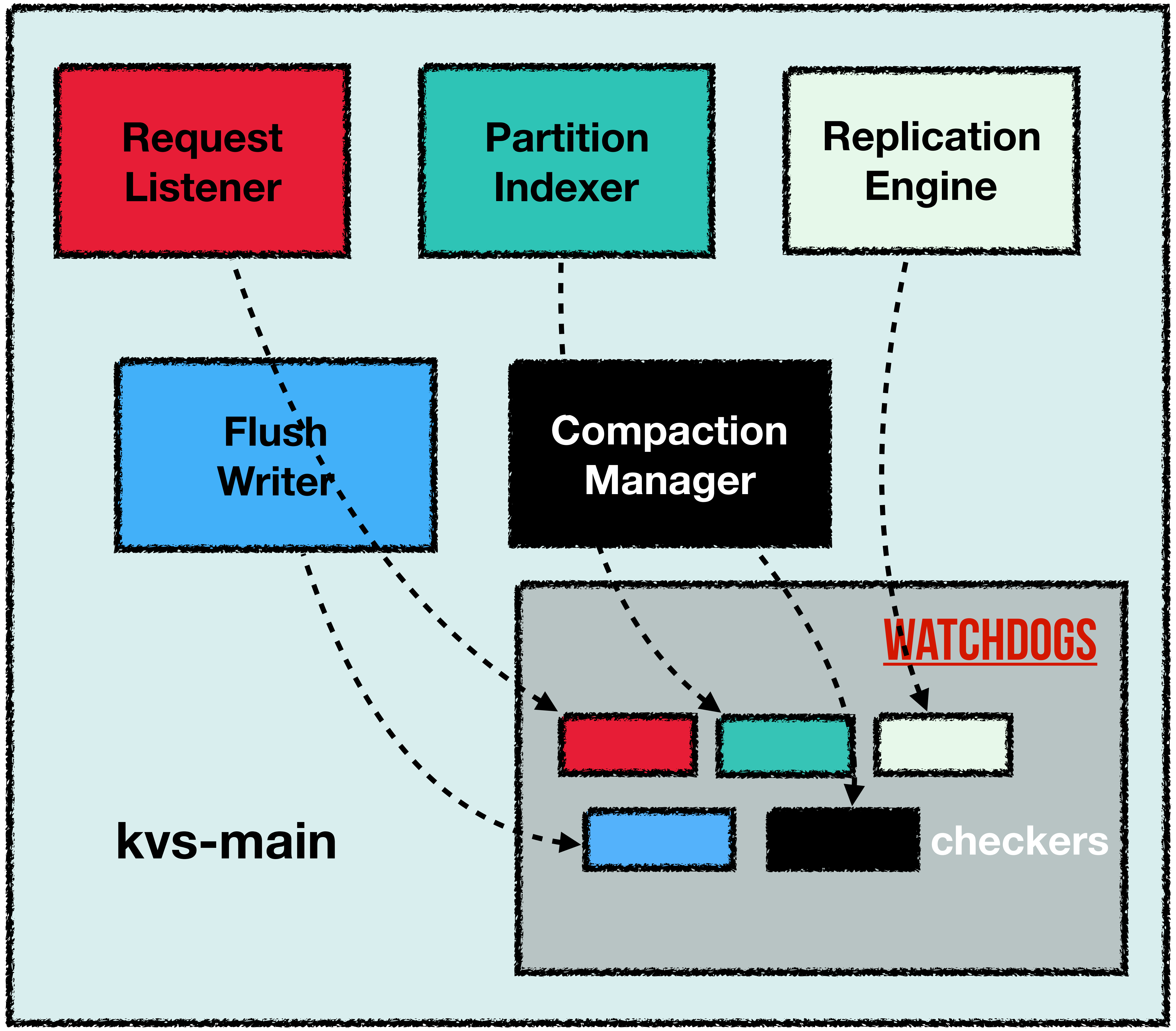
they are essentially equivalent to a crash failure detector + kill policy

Our solution: intrinsic software watchdog



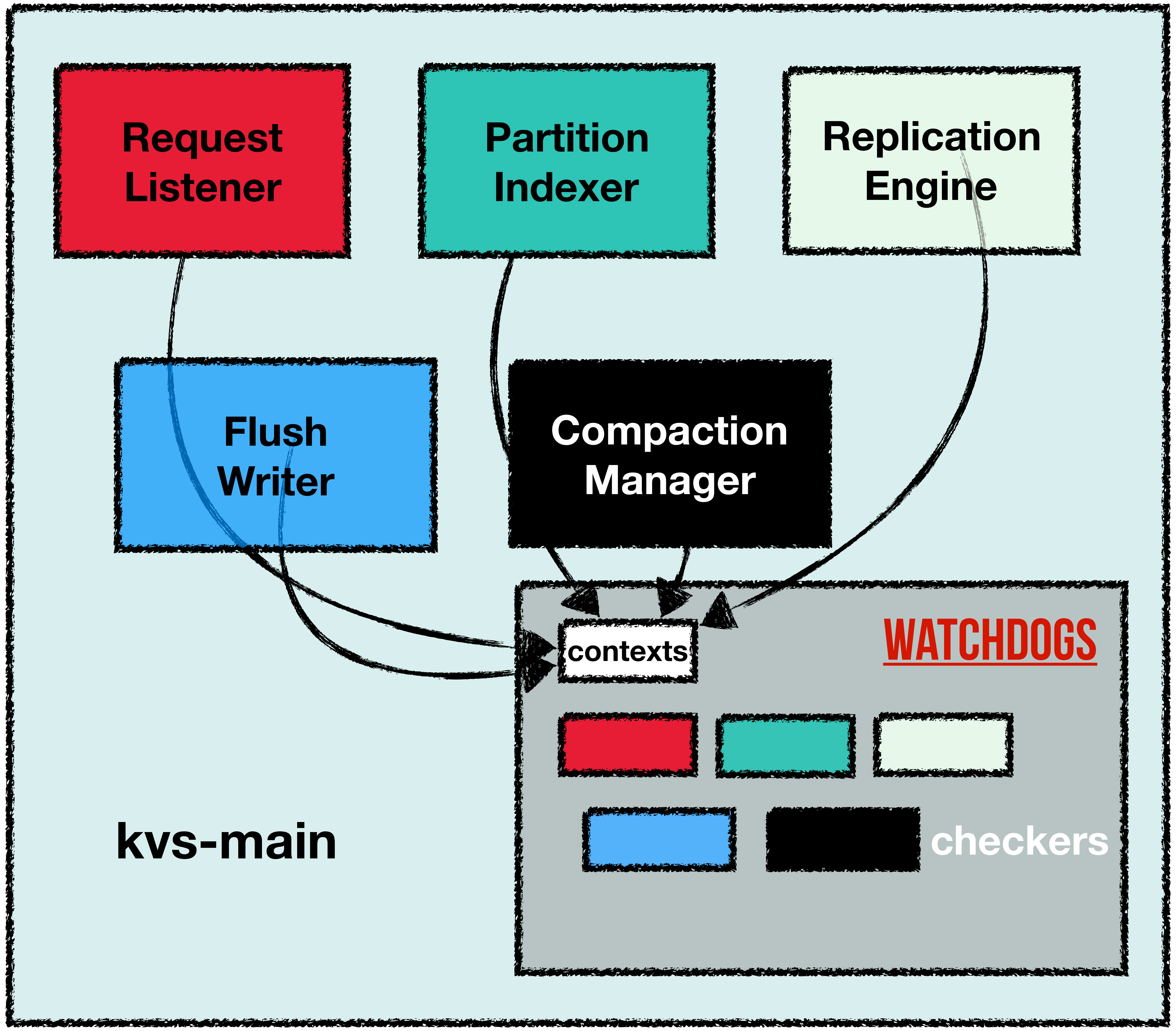
- What should intrinsic software watchdogs look like?

Intrinsic software watchdog



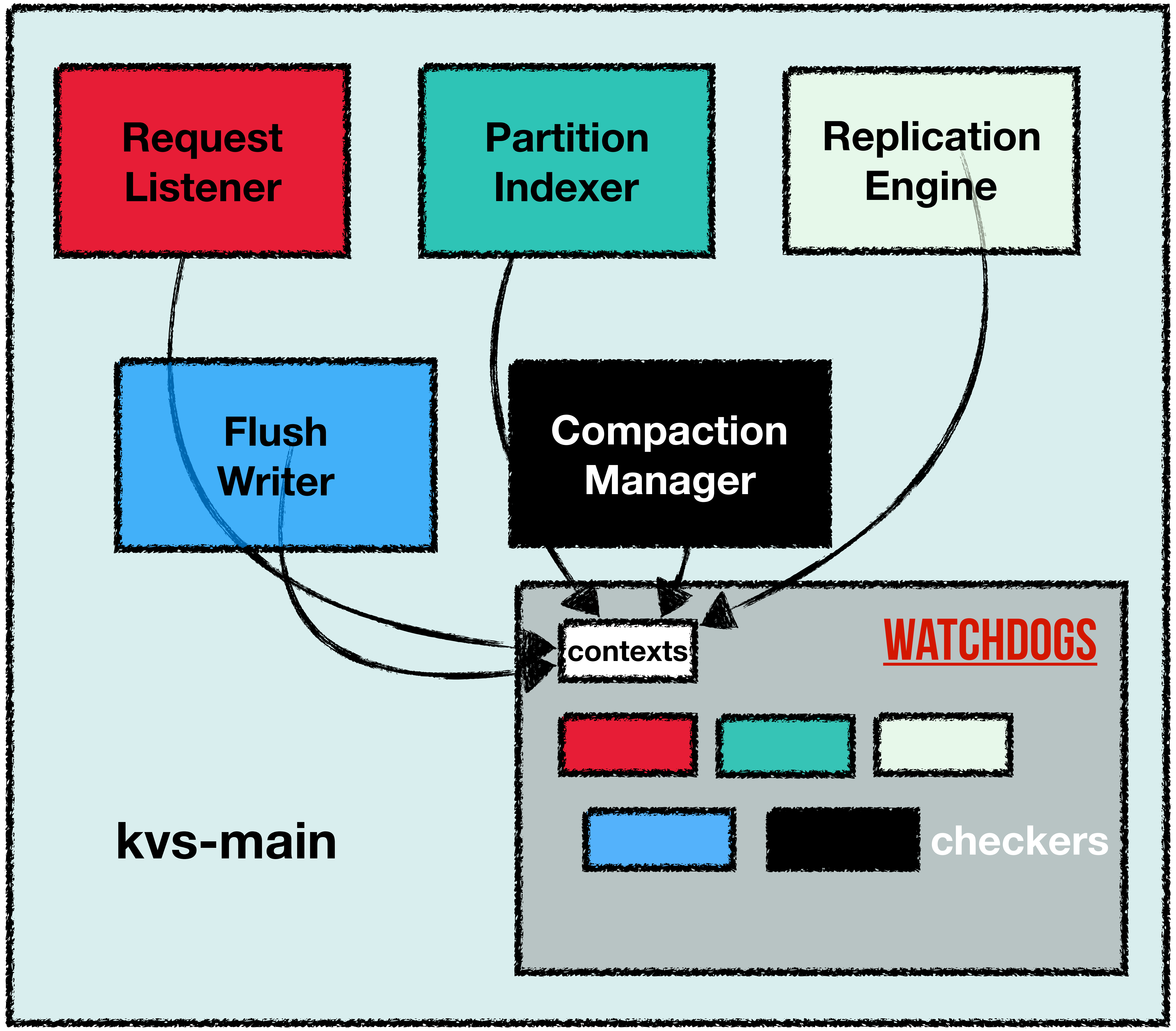
- **Design choice #1 Tailored checker**
  - checkers' logics are customized based on main execution logic

Intrinsic software watchdog



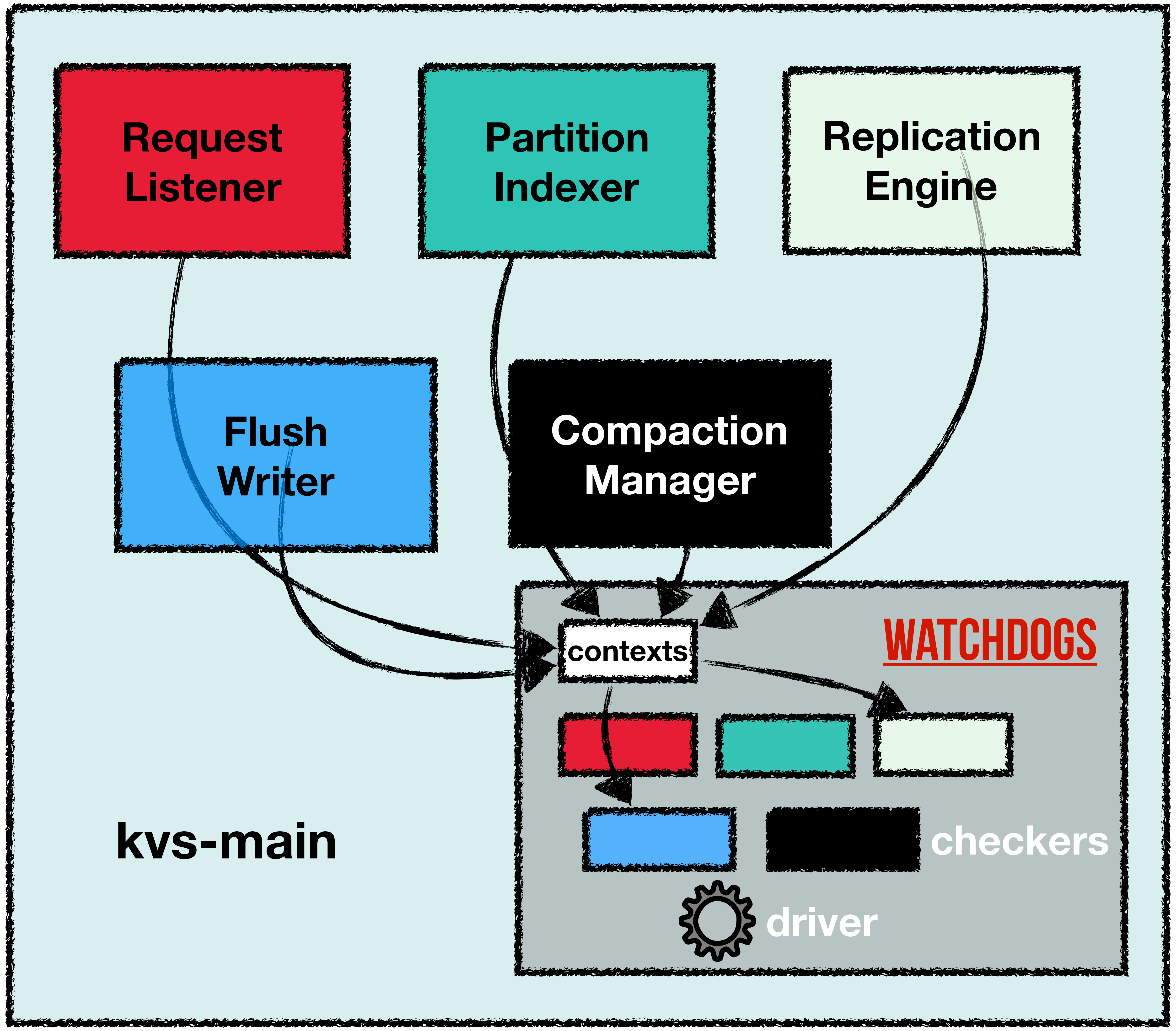
- **Design choice #2 Stateful checker**
  - checkers should faithfully reflect checked target status, which unavoidably requires collecting program states (contexts) from main execution

Intrinsic software watchdog



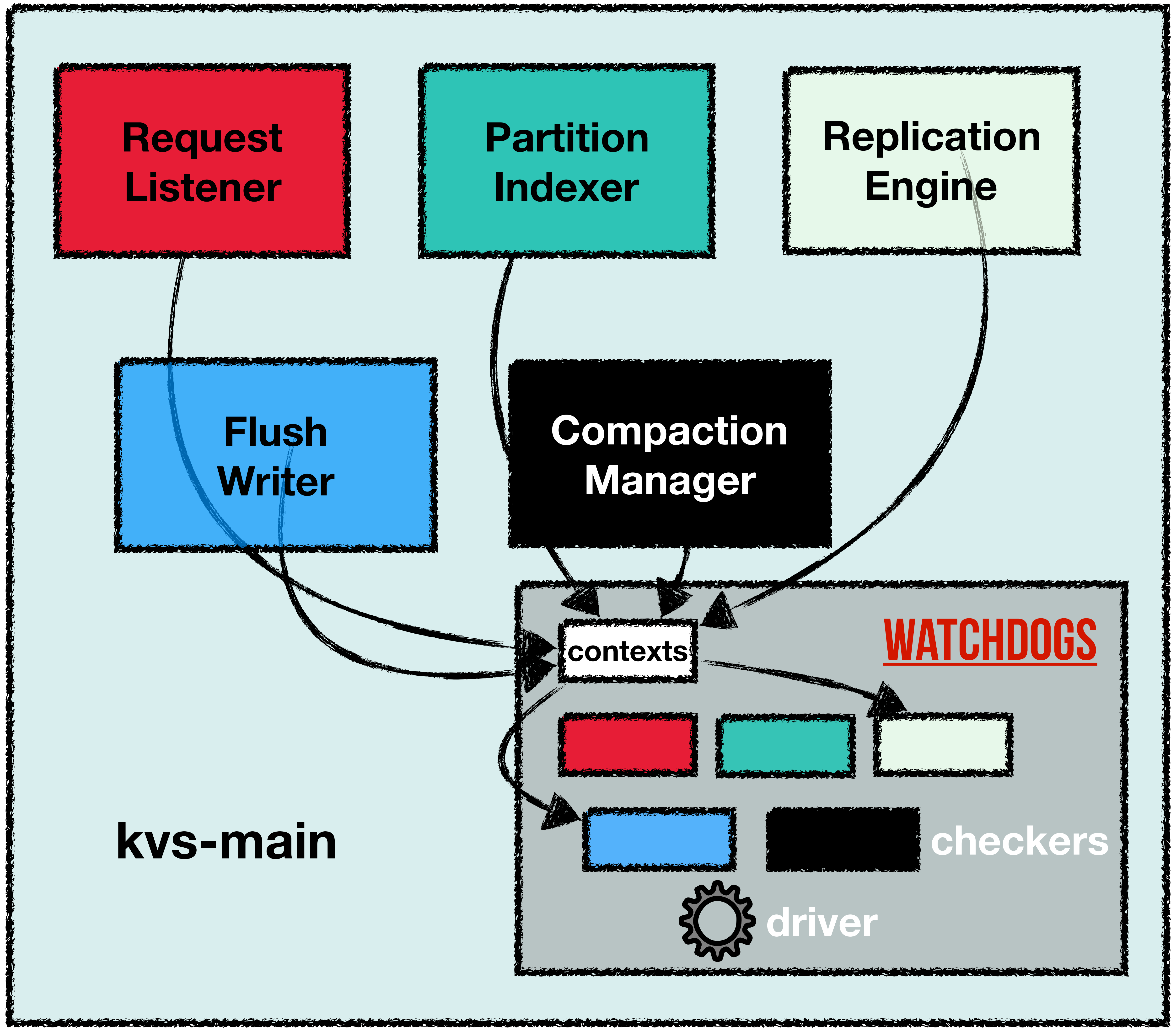
- but with so many customized and stateful checkers, developers have to worry about two things:
  - paying performance penalty in the normal execution even when there is no failure
  - checkers might introduce side effects or alter main execution

Intrinsic software watchdog



- **Design choice #3 Concurrent execution**
  - checkers run async with main execution
  - one-way state synchronization to provide isolation

Proposed intrinsic watchdog abstraction



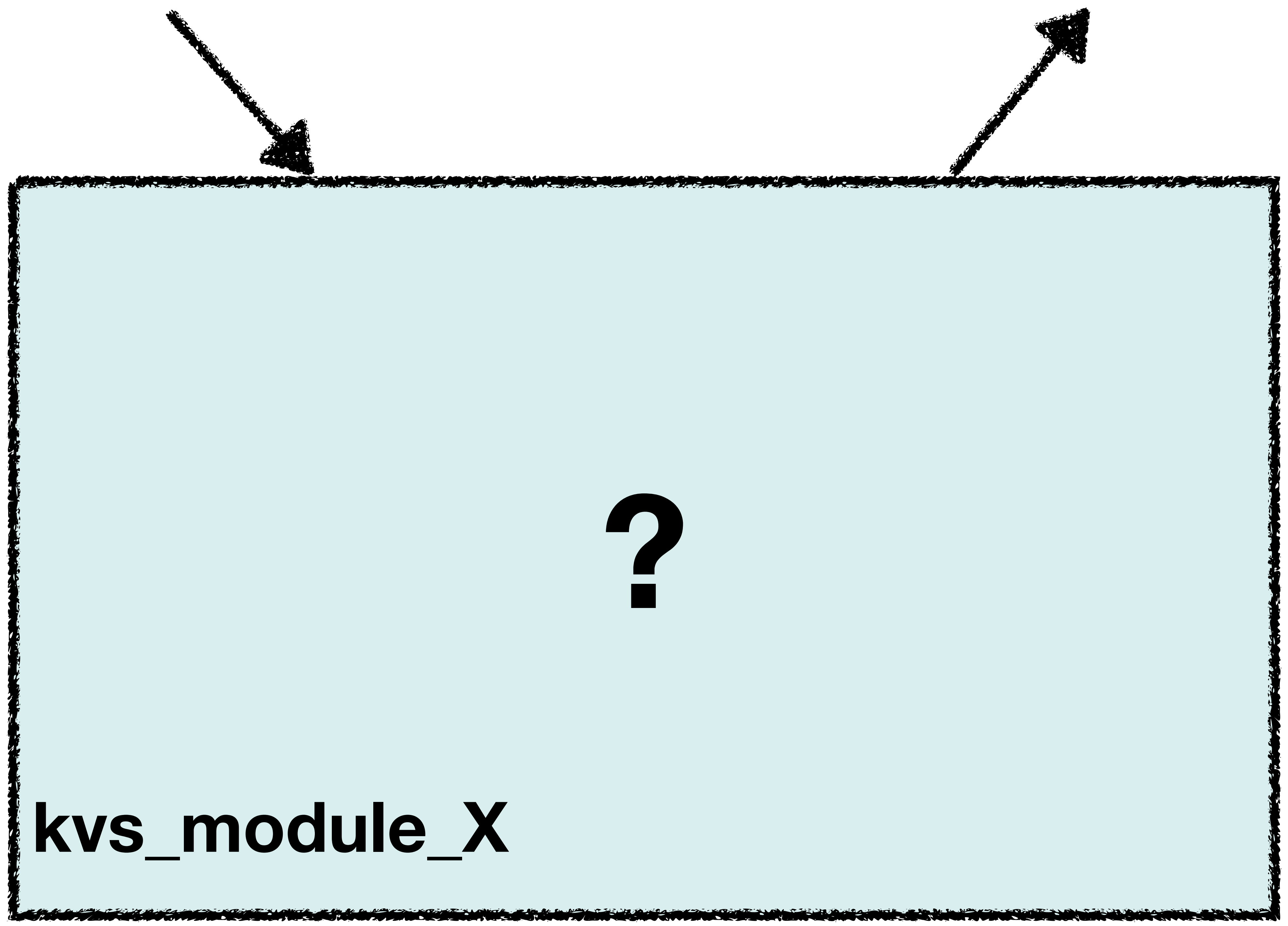
- **Checkers**
  - encapsulated checking procedures
- **Context Manager**
  - synchronize and manage states for checkers
- **Driver**
  - manage checker scheduling and execution

how can we construct watchdog checkers?

Try #1: Probing

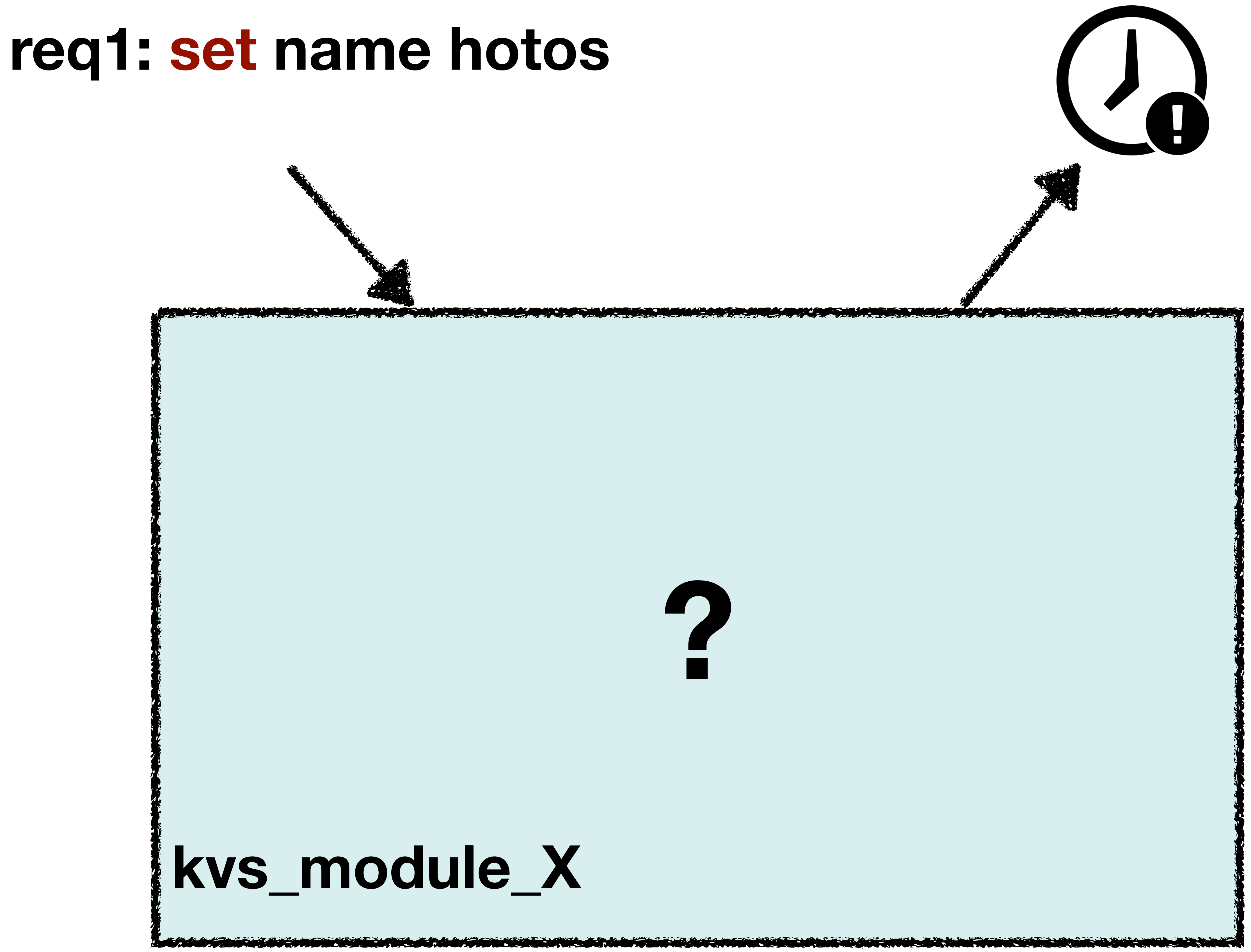
req1: set name hotos
req2: get name

resp1: “OK”
resp2: “hotos”



- periodically invoke some APIs with synthetic input and check
- perfect accuracy
  - no false alarm

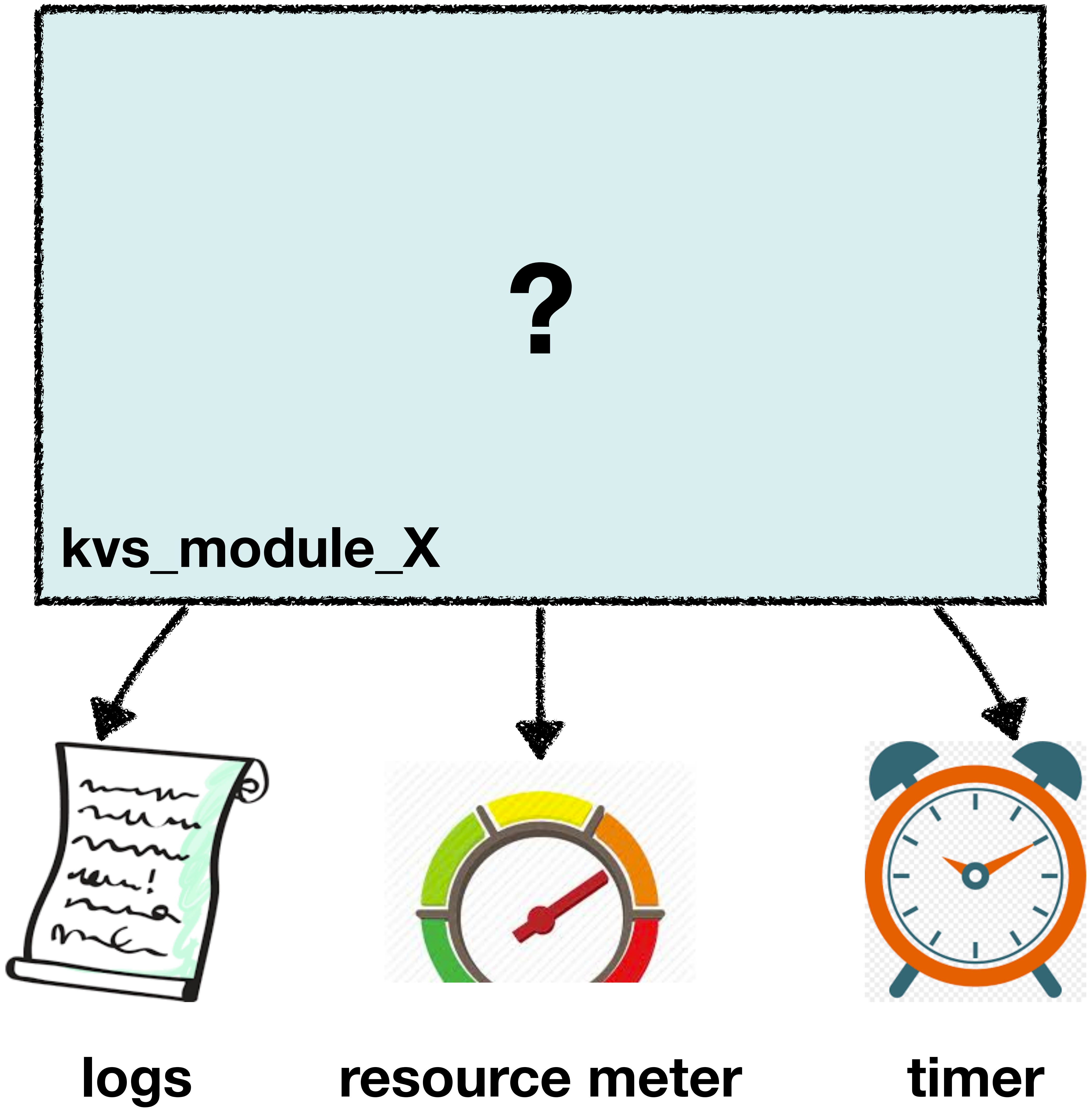
Try #1: Probing



- problem: poor localization
  - e.g. if the response timeouts, we have no idea which step of execution is stuck

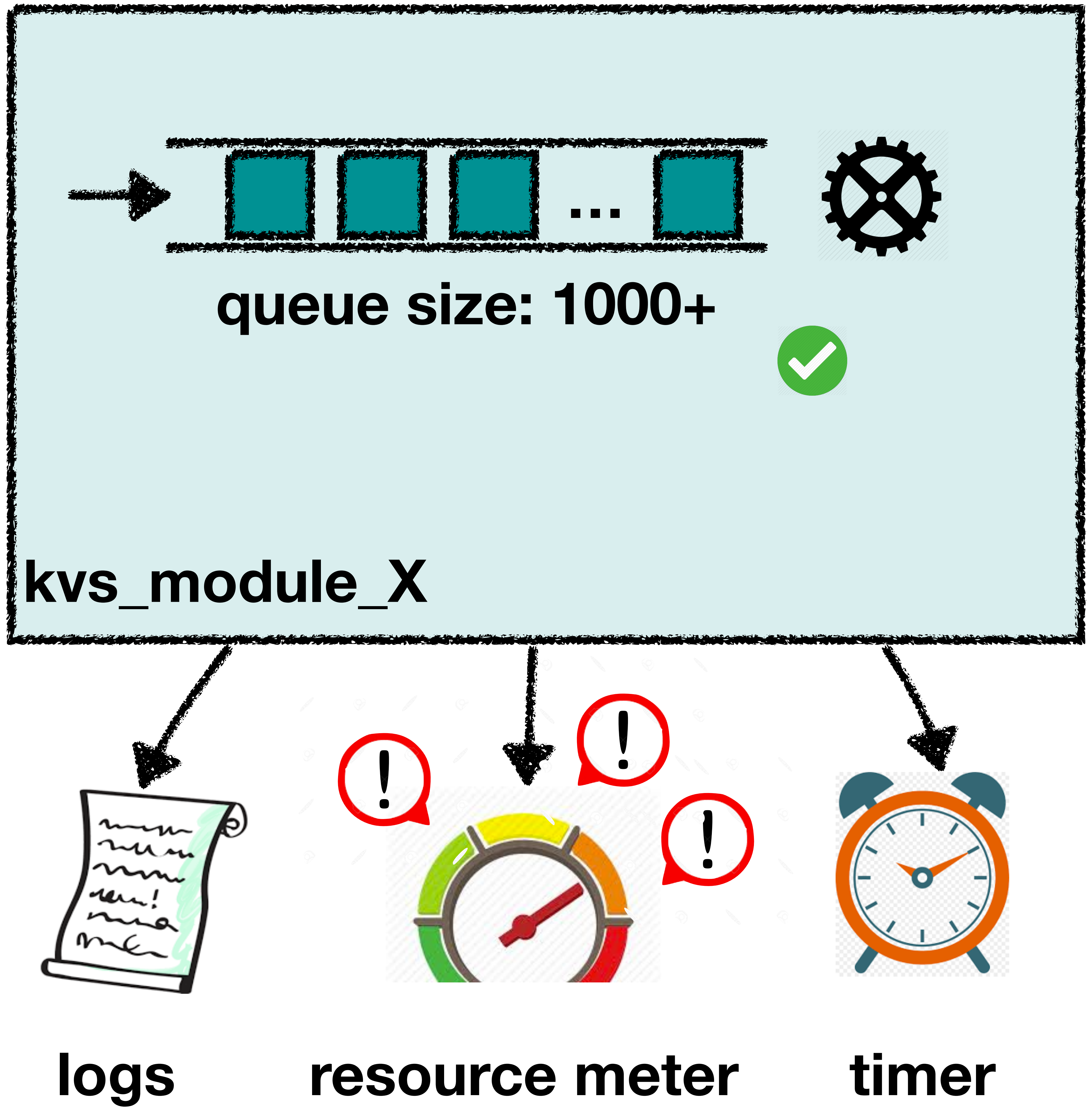
Type	Level	Example	Completeness	Accuracy	Pinpoint
Probe	API	App spy, httpd mod_watchdog	Weak	Perfect	✗

Try #2: Signal



- define some system health indicators and monitor
  - e.g. memory load is high ? logs contain ERRORs? process timeout?

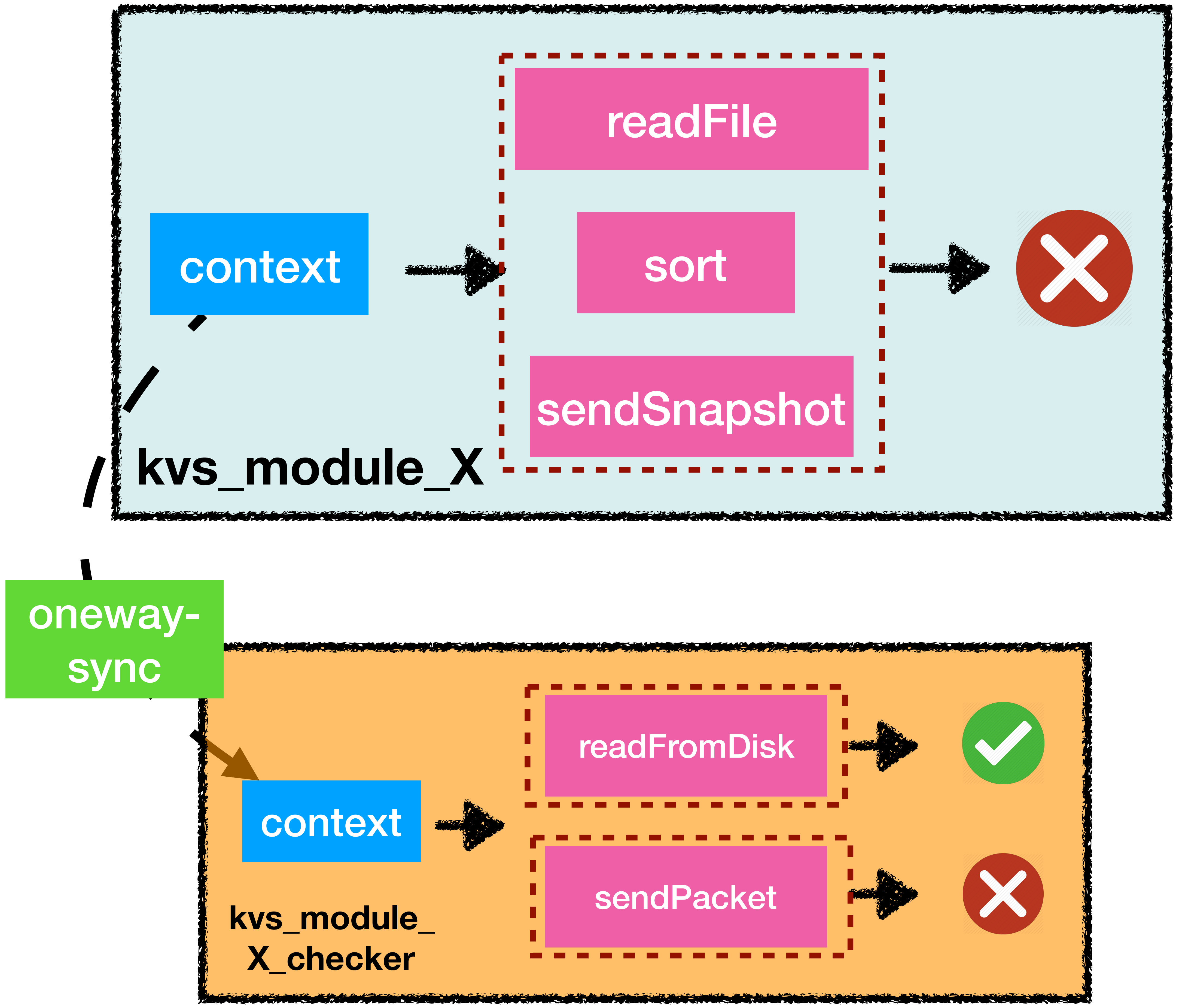
Try #2: Signal



- **problem: weak accuracy**
  - excessive signals causing massive false alarms
  - need significant tuning to be accurate

Type	Level	Example	Completeness	Accuracy	Pinpoint
Probe	API	App spy, httpd mod_watchdog	Weak	Perfect	✗
Signal	Resource	WDT, Linux watchdogd	Modest	Weak	✓

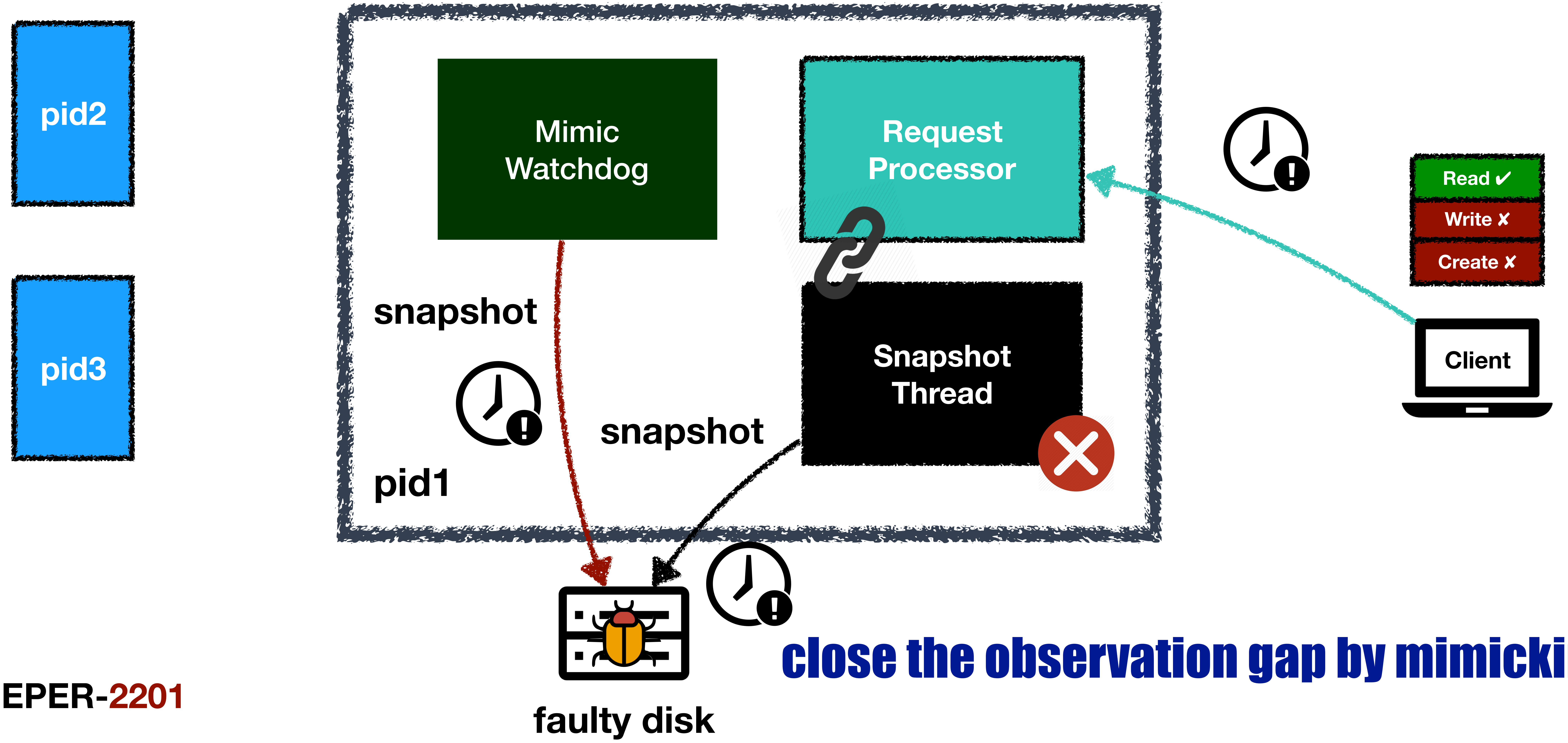
Try #3: Mimic



- imitate what main execution is doing by executing similar operations to expose errors

Type	Level	Example	Completeness	Accuracy	Pinpoint
Probe	API	App spy, httpd mod_watchdog	Weak	Perfect	✗
Signal	Resource	WDT, Linux watchdogd	Modest	Weak	✓
Mimic	Operation	HDFS disk checker (partly)	Strong	Strong	✓

Use mimic checker to detect zookeeper failure



close the observation gap by mimicking!

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Challenges to write mimic-type watchdogs

- **time-consuming for developers to manually write good watchdogs**
  - too many modules and functions to be covered
- **challenging to write it right**
  - e.g. alter the main execution, invoke a dangerous operation

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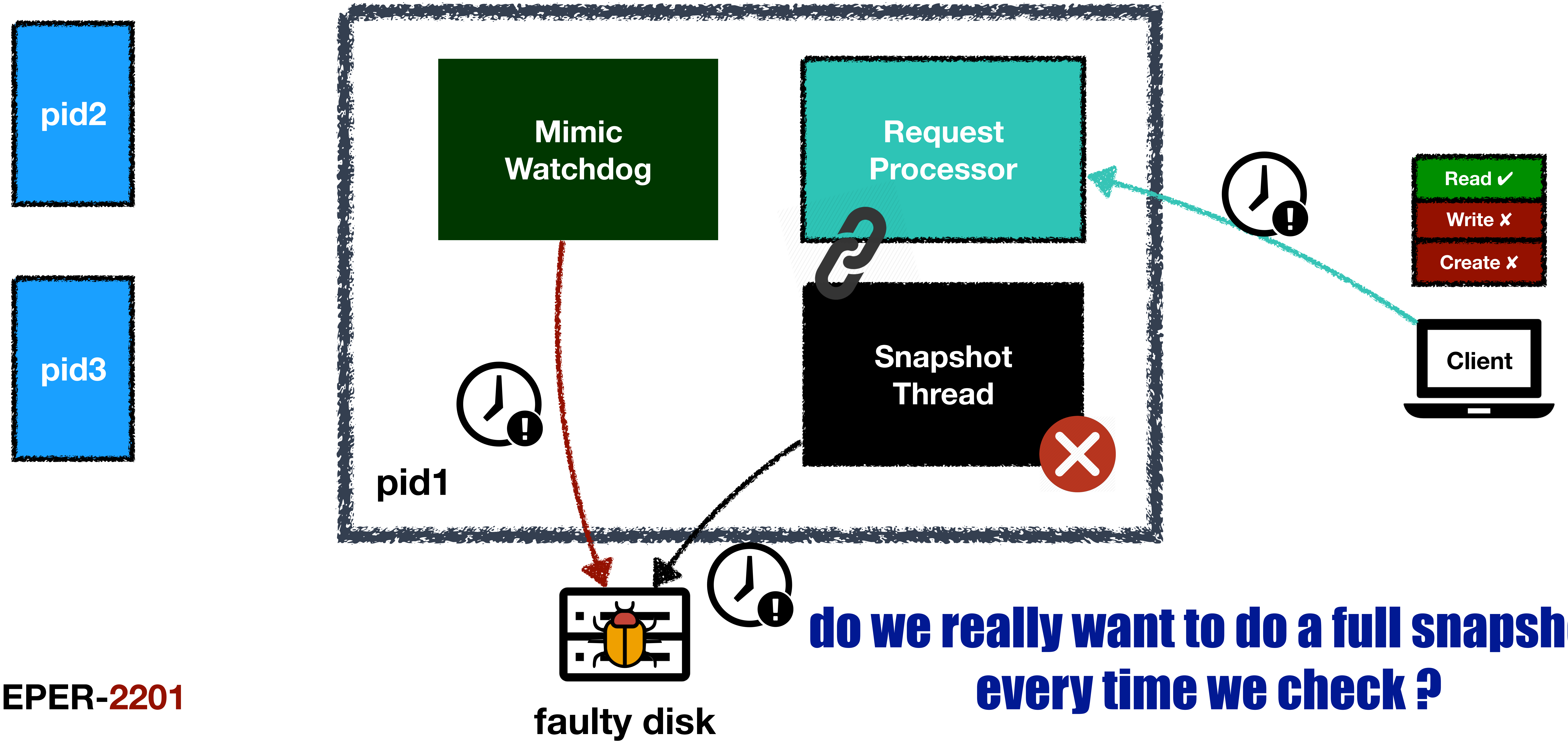
- AutoWatchdog: a tool to generate watchdogs
  - technique: program reduction
- Challenges & Opportunities

Our system

- AutoWatchdog
  - a prototype that systematically generate mimic-type watchdogs for system softwares
  - core technique: program reduction

```
% ./autowd -jar zookeeper-3.4.6.jar -m zookeeper.manifest
analyzing..
generating..
repackaging..
done. Total 1min 6s.
%  ls output/
zookeeper-3.4.6-with-autowd.jar
```

Why do program reduction?



do we really want to do a full snapshot every time we check ?

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1) We should not put everything into checker

```
void serializeNode(OutputArchive oa, StringBuilder path) throws IOException {
    String pathString = path.toString();
    DataNode node = getNode(pathString);

    String children[] = null;
    synchronized (node) {
        oa.writeRecord(node, "node");
        Set<String> childs = node.getChildren();
        if (childs != null)
            children = childs.toArray(new String[childs.size()]);
    }
    path.append('/');
    int off = path.length();
    if (children != null) {
        for (String child : children) {
            path.delete(off, Integer.MAX_VALUE);
            path.append(child);
            serializeNode(oa, path);
        }
    }
}
```

what if put the whole snapshot operation into the checker and run?

1) We should not put everything into checker

```
void serializeNode(OutputArchive oa, StringBuilder path) throws IOException {
    String pathString = path.toString();
    DataNode node = getNode(pathString);

    String children[] = null;
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        Set<String> childs = node.getChildren();
        if (childs != null)
            children = childs.toArray(new String[childs.size()]);
    }
    path.append('/');
    int off = path.length();
    if (children != null) {
        for (String child : children) {
            path.delete(off, Integer.MAX_VALUE);
            path.append(child);
            serializeNode(oa, path);
        }
    }
}
```
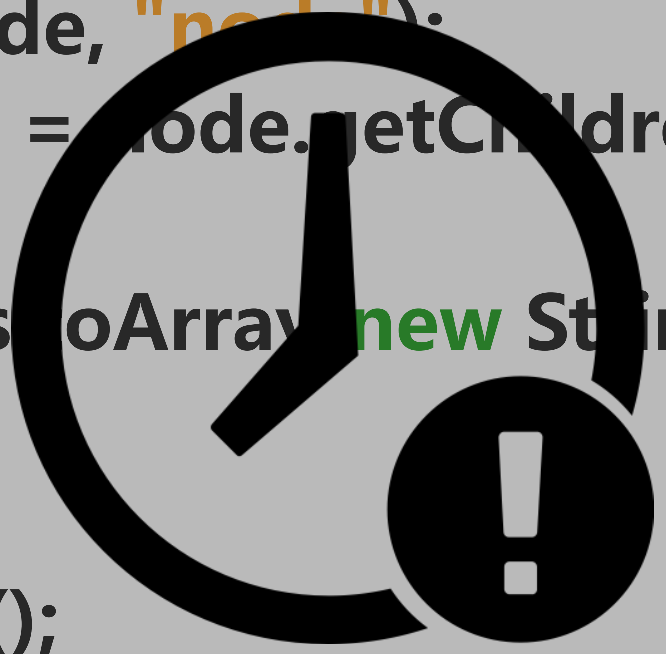
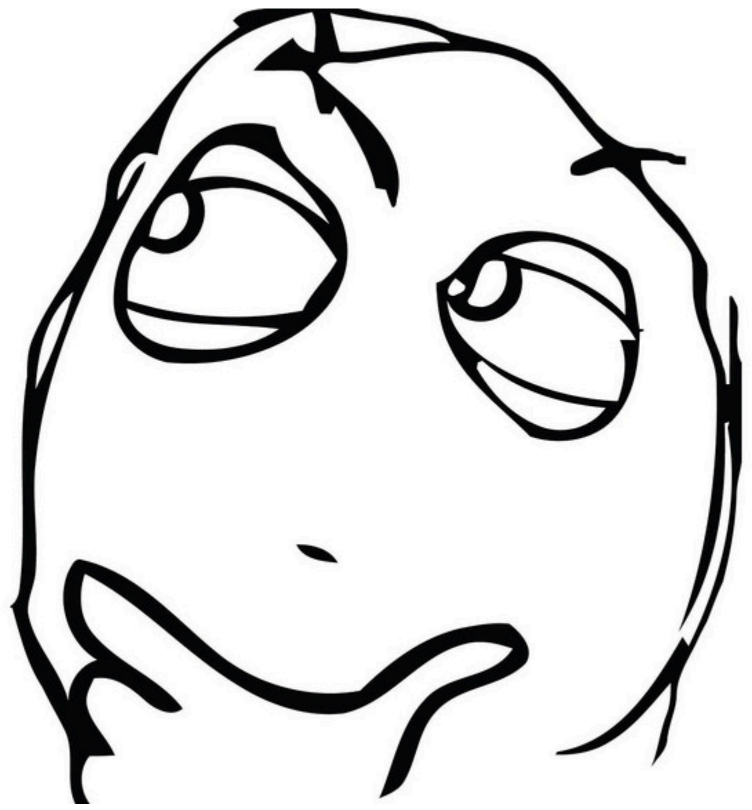





checker can detect the timeout,
but we don't know which part goes wrong

2) We need not put everything into checker

```
void serializeNode(OutputArchive oa, StringBuilder path) throws IOException {
    String pathString = path.toString();
    DataNode node = getNode(pathString);

    String children[] = null;
    synchronized (node) {
        oa.writeRecord(node, "node");
        Set<String> childs = node.getChildren();
        if (childs != null)
            children = childs.toArray(new String[childs.size()]);
    }
    path.append('/');
    int off = path.length();
    if (children != null) {
        for (String child : children) {
            path.delete(off, Integer.MAX_VALUE);
            path.append(child);
            serializeNode(oa, path);
        }
    }
}
```

2) We need not put everything into checker

```
void serializeNode(OutputArchive oa, StringBuilder path) throws IOException {
    String pathString = path.toString();
    DataNode node = getNode(pathString);

    String children[] = null;
    synchronized (node) {
        oa.writeRecord(node, "node");
        Set<String> childs = node.getChildren();
        if (childs != null)
            children = childs.toArray(new String[childs.size()]);
    }
    path.append('/');
    int off = path.length();
    if (children != null) {
        for (String child : children) {
            path.delete(off, Integer.MAX_VALUE);
            path.append(child);
            serializeNode(oa, path);
        }
    }
}
```

convert string

convert array

append path

iterate children
and modify path

a lot of operations are logically deterministic and should be checked before production

2) We need not put everything into checker

```
void serializeNode(OutputArchive oa, StringBuilder path) throws IOException {
    String pathString = path.toString();
    DataNode node = getNode(pathString);

    String children[] = null;
    synchronized (node) {
        oa.writeRecord(node, "node");
        Set<String> childs = node.getChildren();
        if (childs != null)
            children = childs.toArray(new String[childs.size()]);
    }
    path.append('/');
    int off = path.length();
    if (children != null) {
        for (String child : children) {
            path.delete(off, Integer.MAX_VALUE);
            path.append(child);
            serializeNode(oa, path);
        }
    }
}
```

do I/O + in synchronized block

some operations are more vulnerable in the production environment

Program reduction

- **Given a program P, create a watchdog W that can detect gray failures in P without imposing on P's execution.**
- **Five steps**
  - #1 locate long-running regions
  - #2 reduce the program
  - #3 locate vulnerable operations
  - #4 encapsulate watchdog checkers
  - #5 insert watchdog hooks

Step#1 locate long-running regions

```java
@Override
public void run() {
    try {
        int logCount = 0;

        // we do this in an attempt to ensure that not all of the servers
        // in the ensemble take a snapshot at the same time
        setRandRoll(r.nextInt( bound: snapCount/2));
        while (true) {
            Request si = null;
            if (toFlush.isEmpty()) {
                si = queuedRequests.take();
            } else {
                si = queuedRequests.poll();
                if (si == null) {
                    flush(toFlush);
                    continue;
                }
            }
            if (si == requestOfDeath) {
                break;
            }
            if (si != null) {
                // track the number of records written to the log
                if (zks.getZKDatabase().append(si)) {
                    logCount++;
                    if (logCount > (snapCount / 2 + randRoll)) {
                        randRoll = r.nextInt( bound: snapCount/2);
                        // roll the log
                        zks.getZKDatabase().rollLog();
                        // take a snapshot
                        if (snapInProcess != null && snapInProcess.isAlive()) {
                            LOG.warn("Too busy to snap, skipping");
                        } else {
                            new Error().printStackTrace();
                            snapInProcess = new Thread( name: "Snapshot Thread") {
                                    public void run() {
                                        try {
                                            zks.takeSnapshot();
                                        } catch(Exception e) {
                                            LOG.warn("Unexpected exception", e);
                                        }
                                    }
                                };
                            snapInProcess.start();
                        }
                        logCount = 0;
                    }
                } else if (toFlush.isEmpty()) {
                    // optimization for read heavy workloads
                    // iff this is a read, and there are no pending
                    // flushes (writes), then just pass this to the next
                    // processor
                    if (nextProcessor != null) {
                        nextProcessor.processRequest(si);
                        if (nextProcessor instanceof Flushable) {
                            ((Flushable)nextProcessor).flush();
                        }
                    }
                    continue;
                }
                toFlush.add(si);
                if (toFlush.size() > 1000) {
                    flush(toFlush);
                }
            }
        }
    } catch (Throwable t) {
        LOG.error("Severe unrecoverable error, exiting", t);
        running = false;
        System.exit( status: 11);
    }
    LOG.info("SyncRequestProcessor exited!");
}
```

Step#1 locate long-running regions

```
public class SyncRequestProcessor {
  public void run() {
   int logCount = 0;

   setRandRoll(r.nextInt(snapCount/2));
   ...
    while (running) {
     ...
     if (logCount > (snapCount / 2 ))
      zks.takeSnapshot();
    }
    ..
    LOG.info("SyncRequestProcessor exited!");
  }
```

initialization stage

long-running stage

cleanup stage

Step#2 reduce the program

```
public class SyncRequestProcessor {
  public static void serializeSnapshot(DataTree dt, ...) {

    ...
    dt.serialize(oa, “tree”);
  }
}
public class DataTree{
  public void serialize(OutputArchive oa, String tag) {
    scout = 0;
    serializeNode(oa, new StringBuilder(“”));
    ...
}
```

keep reducing

keep reducing

Step#3 locate vulnerable operations

```
void serializeNode(OutputArchive oa, StringBuilder path) throws IOException {
    String pathString = path.toString();
    DataNode node = getNode(pathString);

    String children[] = null;
    synchronized (node) {
        oa.writeRecord(node, "node");
        Set<String> childs = node.getChildren();
        if (childs != null)
            children = childs.toArray(new String[childs.size()]);
    }
    path.append('/');
    int off = path.length();
    ...
}
```

vulnerable op found, mark

our heuristic

I/O,
synchronization, resource,
communication related
method invocations,
...

Step#4 encapsulate watchdog checkers

```
public class SyncRequestProcessor$Checker {
 public static void serializeNode_reduced(OutputArchive arg0, DataNode arg1) {
  try{
   arg0.writeRecord(arg1, “node”);
  } catch (Throwable ex)
  …
 }
 public static Status checkTargetFunction0() {
  …
  Context ctx = ContextFactory.serializeNode_reduced_context();
  if (ctx.status == READY) {
   OutputArchive arg0 = ctx.args_getter(0);
   DataNode arg1 = ctx.args_getter(1);
   executor.runAsyncWithTimeout(serializeSnapshot_reduced(arg0, arg1), TIMEOUT);
  }
  else
   LOG.debug(“checker context not ready”);
  …
 }
}
```

extracted vulnerable operations

Step#5 insert watchdog hooks

```
void serializeNode(OutputArchive oa, StringBuilder path) throws IOException {
    String pathString = path.toString();
    DataNode node = getNode(pathString);
                    + ContextFactory.serializeNode_context_setter(oa, node);
    String children[] = null;
    synchronized (node) {
        oa.writeRecord(node, "node");
        Set<String> childs = node.getChildren();
        if (childs != null)
            children = childs.toArray(new String[childs.size()]);
    }
    path.append('/');
    int off = path.length();
    ...
}
```

insert context hook before vulnerable operation

Preliminary results

- **AutoWatchdog**:
  - **based on Soot and supports Java programs**
  - **applied to Zookeeper, HDFS, Cassandra**
  - **successfully detected ZooKeeper-2201 failure in ~7 seconds**
    - with blocked function pinpointed and concrete context captured
  - **with moderate performance overhead of 7.2 % averagely**
    - compared to 1.5% for the probing checker

Outline

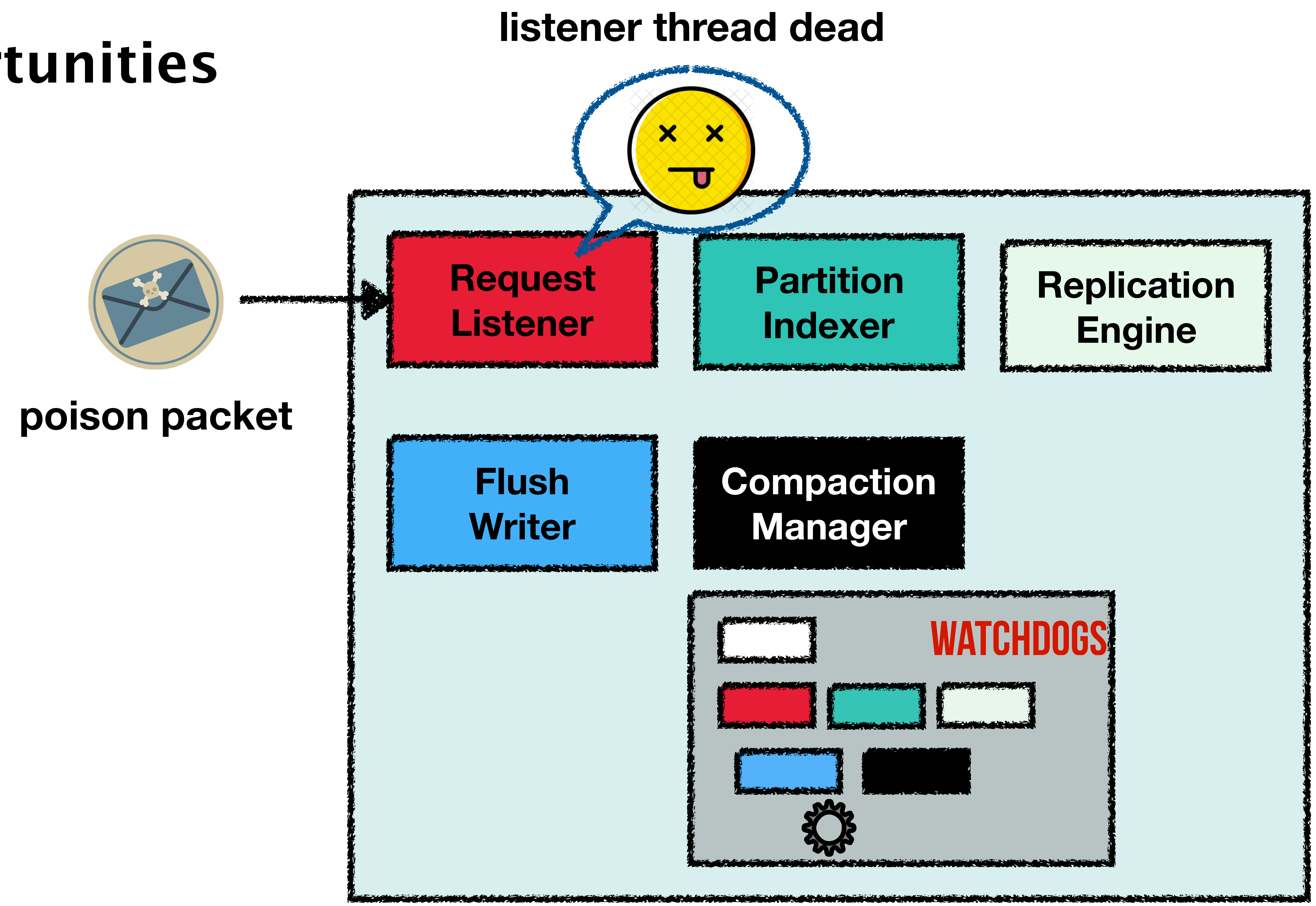
- Motivation
- Intrinsic software watchdog abstraction
  - hardware & software watchdogs
  - characteristics
  - checker approach
- AutoWatchdog: a tool to generate watchdogs
  - technique: program reduction
- Challenges & Opportunities

Discussion

- **Challenges**
  - **locating vulnerable operations is heuristic based**
    - a more principled algorithm to select vulnerable operations?
  - **assess the impact of the detected fault**
    - invoke a validator (probing?) upon failure detection?
  - **semantic checks (fsck-like checks)**
    - leverage test cases to mine semantic checks?

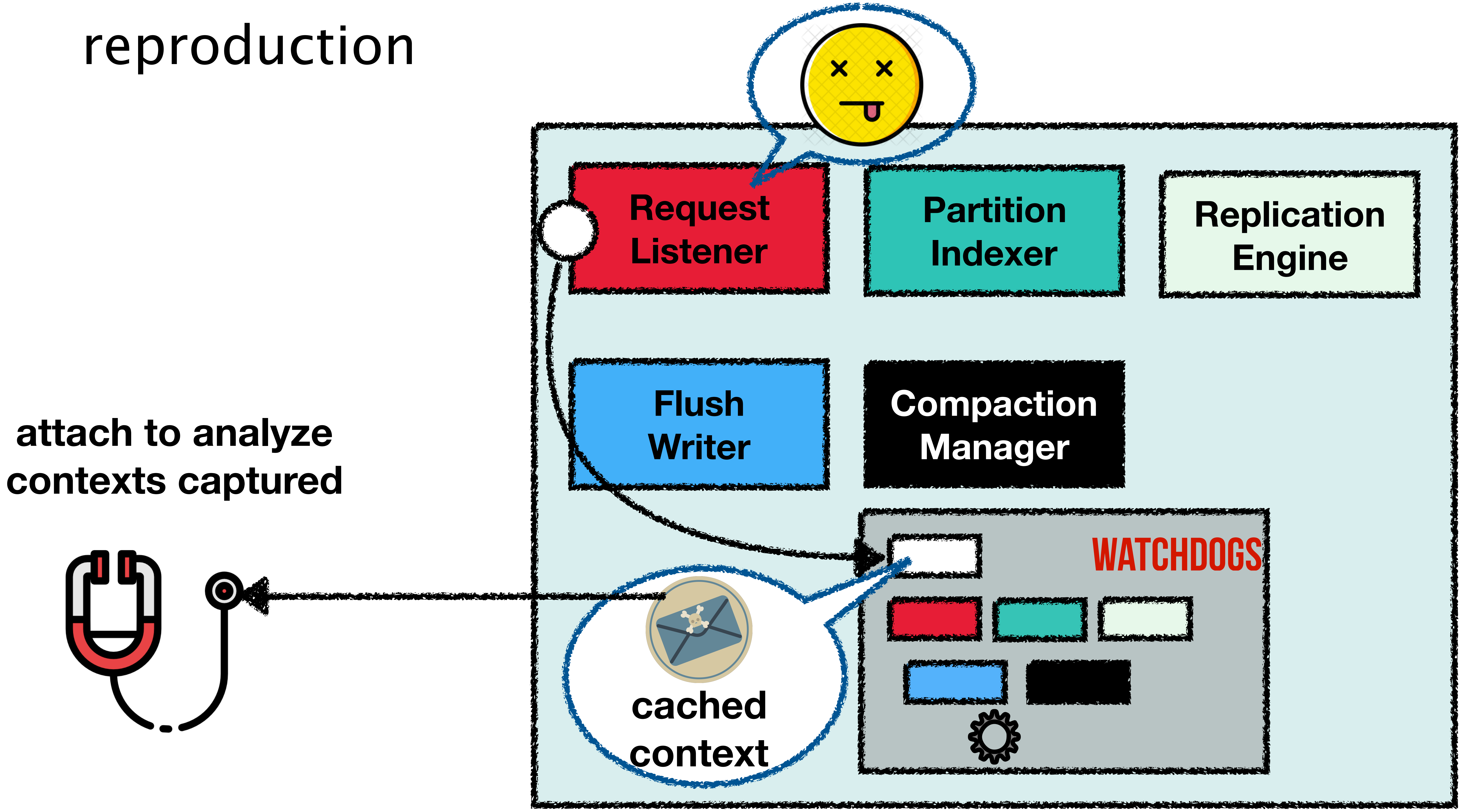
Discussion

- Opportunities



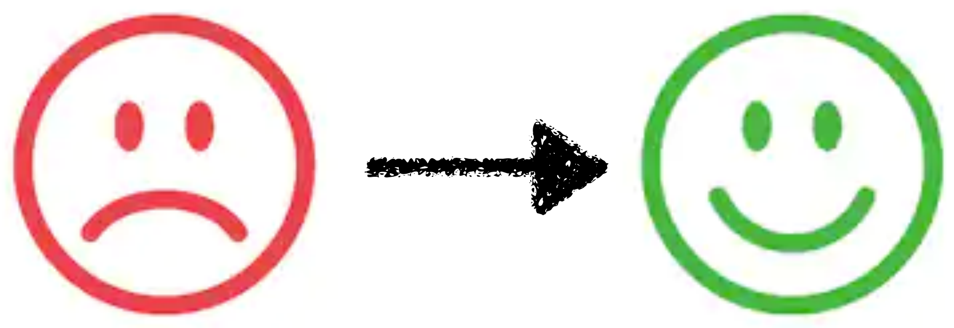
Discussion

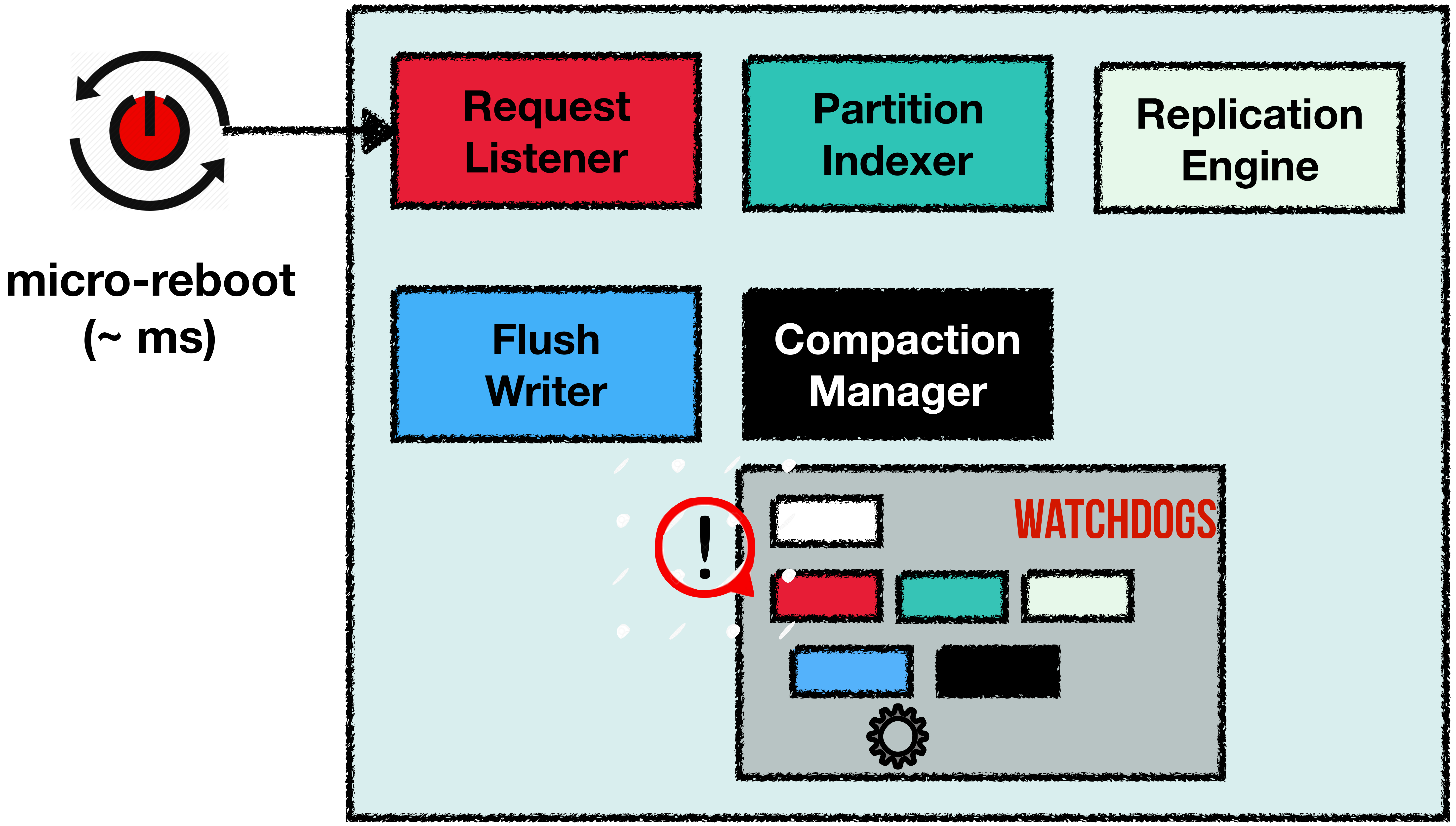
- **Opportunities**
  - leverage contexts captured by the watchdogs for failure reproduction



Discussion

- Opportunities
  - cheap recovery





Conclusion

- **Modern software are increasingly complex and often fail partially**
  - these subtle failures cannot be detected by process-level failure detectors
- **We propose an intrinsic software watchdog abstraction**
  - three characteristics: tailored, stateful and concurrent checkers
- **Mimic-type checkers expose failures by imitating main program**
  - good accuracy, completeness and localization, but challenging to write manually
- **AutoWatchdog generates intrinsic watchdogs with mimic checkers**
  - core technique: program reduction