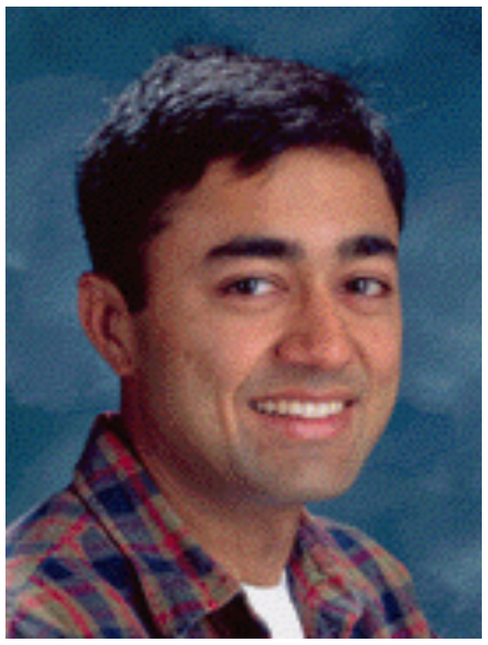
Uncovering Bugs in Distributed Storage Systems During Testing (not in Production!)

Pantazis Deligiannis
Imperial College London

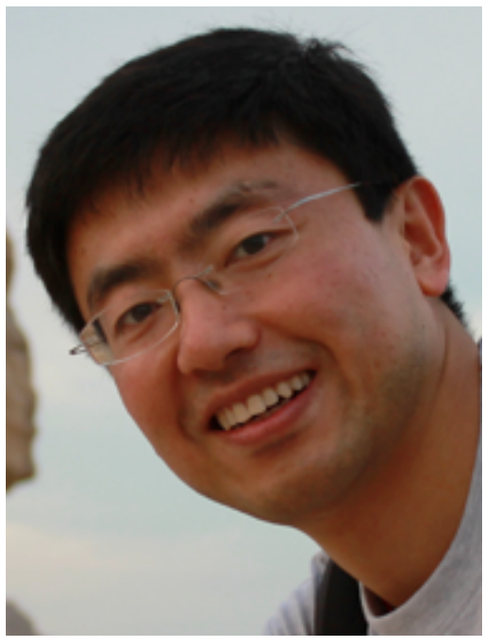
Imperial College London

Microsoft Research

Akash Lal



Shaz Qadeer



Cheng Huang

Wolfram Schulte

Shuo Chen

Alastair Donaldson

Paul Thomson

Rashmi Mudduluru

Matt McCutchen

John Erickson

Top Problem in Distributed Storage Systems: Testing Coverage

- "Due to limited testing coverage, many correctness problems are only exposed in production through live-sites"
- "Engineering overhead extremely high to identify problems"
- "Practical tools that can improve testing coverage highly appreciated!"

– technical leaders and senior managers in Azure Storage

But why programming and testing distributed systems is so HARD?

unreliable network leading to message/data loses

races in the asynchronous interaction between system components

Many sources of nondeterminism cause subtle (but serious) bugs that are hard to detect, diagnose and fix

unexpected failures, timeouts, etc

Today, to find these bugs, engineering teams use:

- Design reviews
- Code reviews
- Unit testing
- Integration testing
- Stress testing
- …

Case Study in Microsoft:
Testing Azure Storage vNext

Microsoft Azure Storage

Durable, highly available, massively scalable cloud storage solution

10s PB in 2010 → now EB

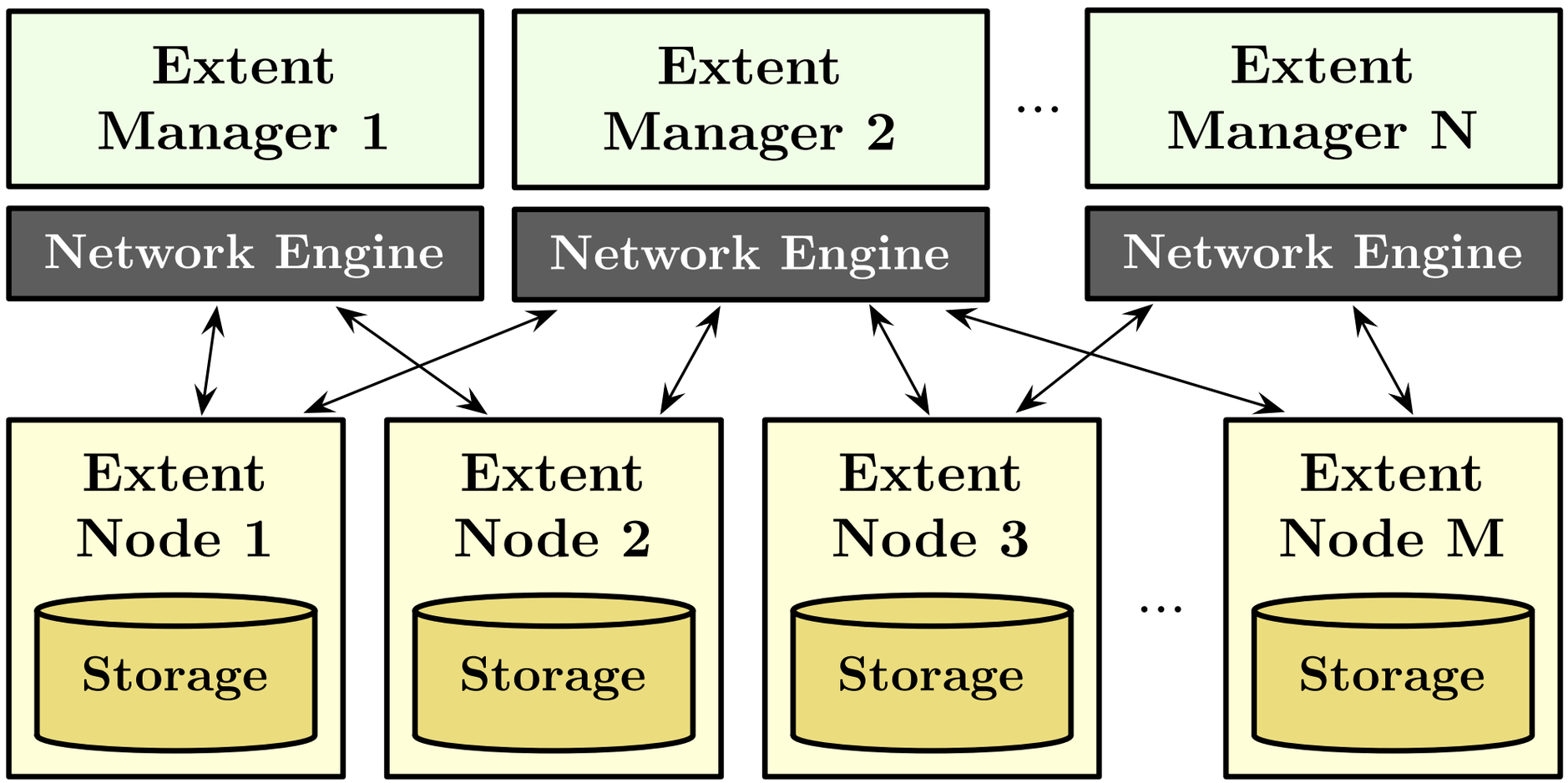
60+ trillion objects

Paxos-based, centralized metadata management

Microsoft Azure Storage vNext

New architecture to scale Azure Storage capacity by >100x

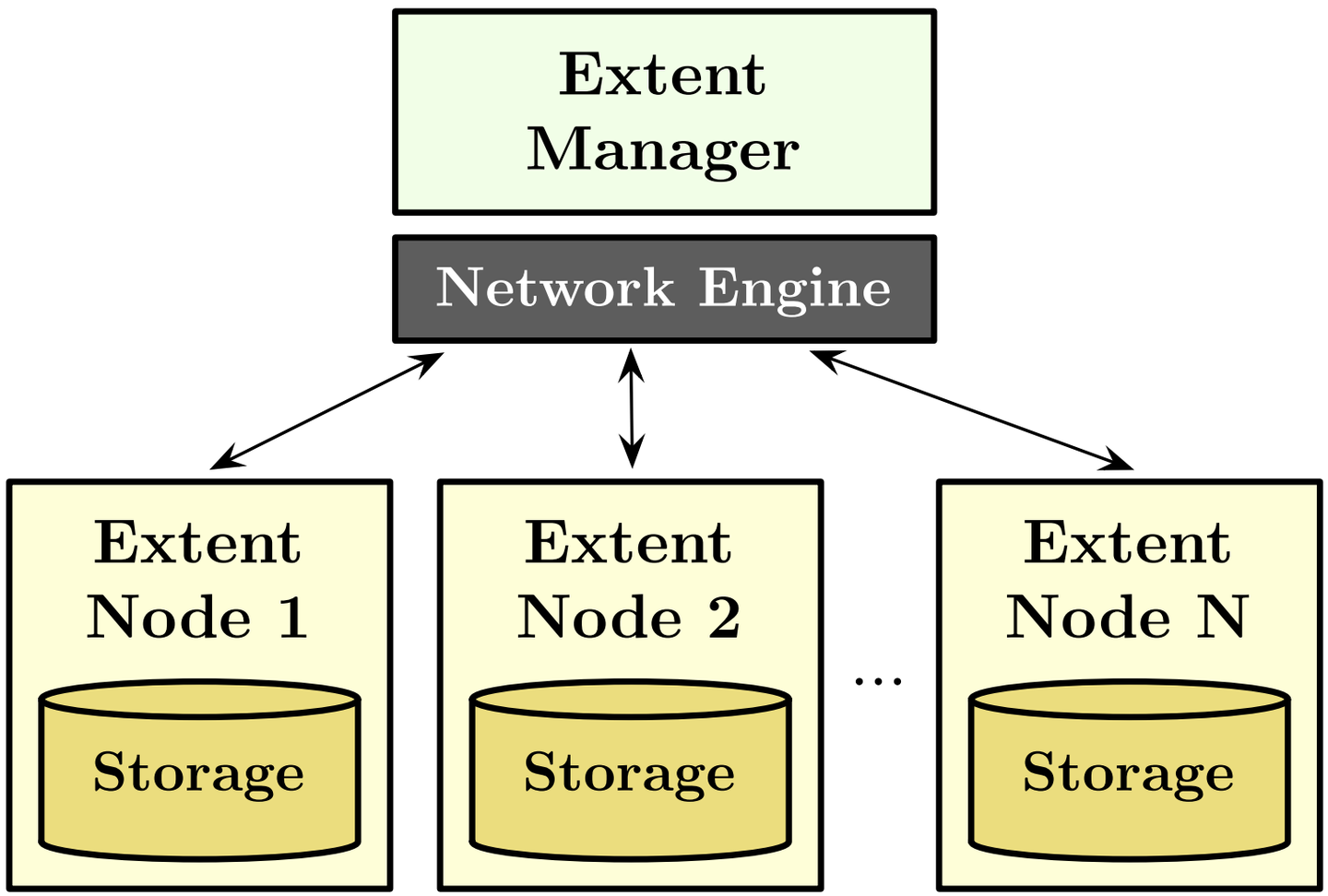
- Completely distributed and fully scale-out metadata management system
- Data stored in extents (GB per extent) — extent space partitioned
- Extent Nodes are managed by light-weight, distributed Extent Managers



Microsoft Azure Storage vNext

- One of the key tasks of Extent Manager is to maintain the replicas

- In this case study we focus on testing the replication logic — very important as we do not want to lose customer data!



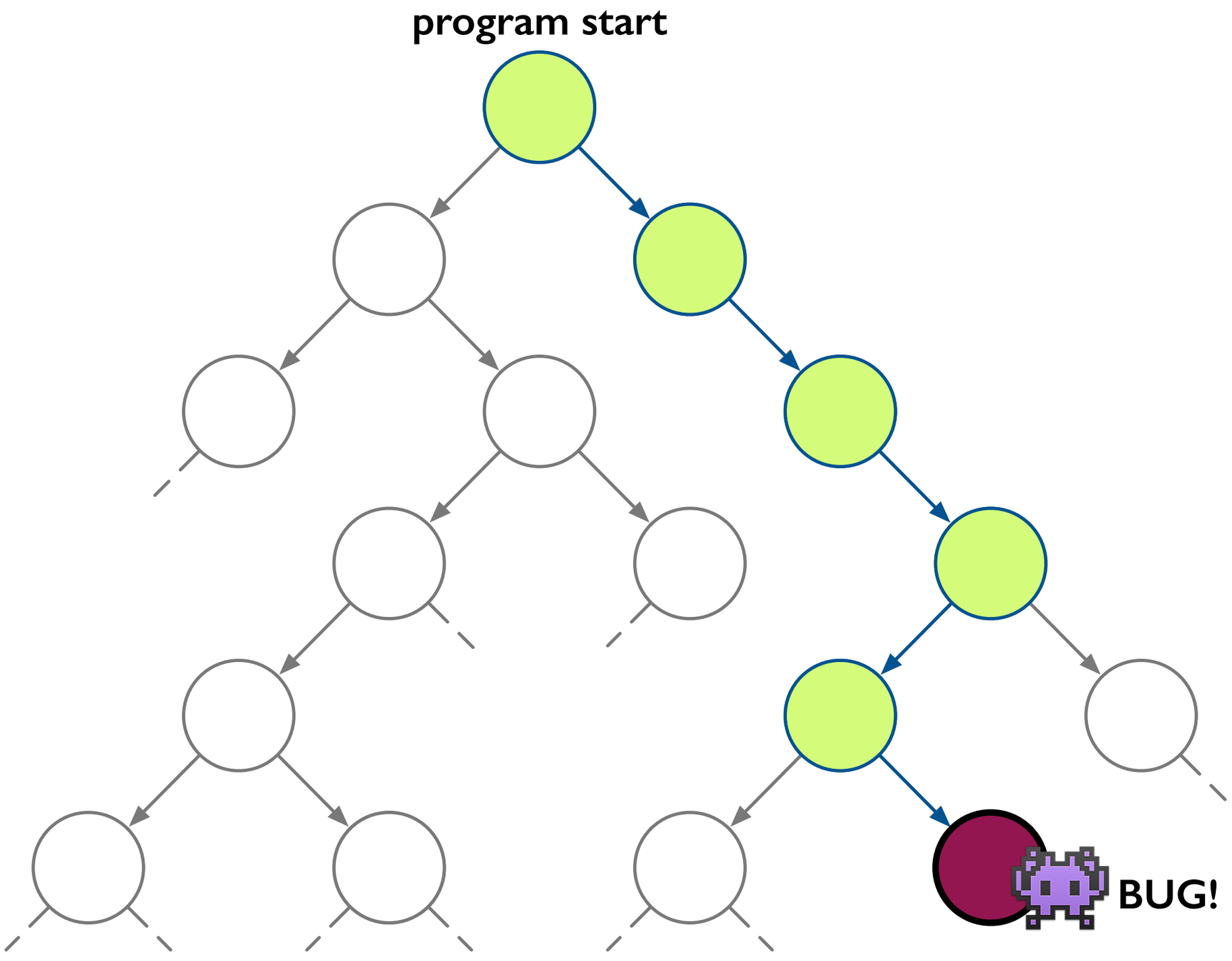
Difficulty in Testing

- Unit tests — always pass
- Integration tests — always pass
  - Launch Extent Manager and Extent Nodes
  - Kill EN and launch new EN → test extents repaired
- Stress tests — fail from time to time
  - ENs are constantly killed and launched
  - replication process gets stuck
  - hard to figure out why — too many logs accumulated!

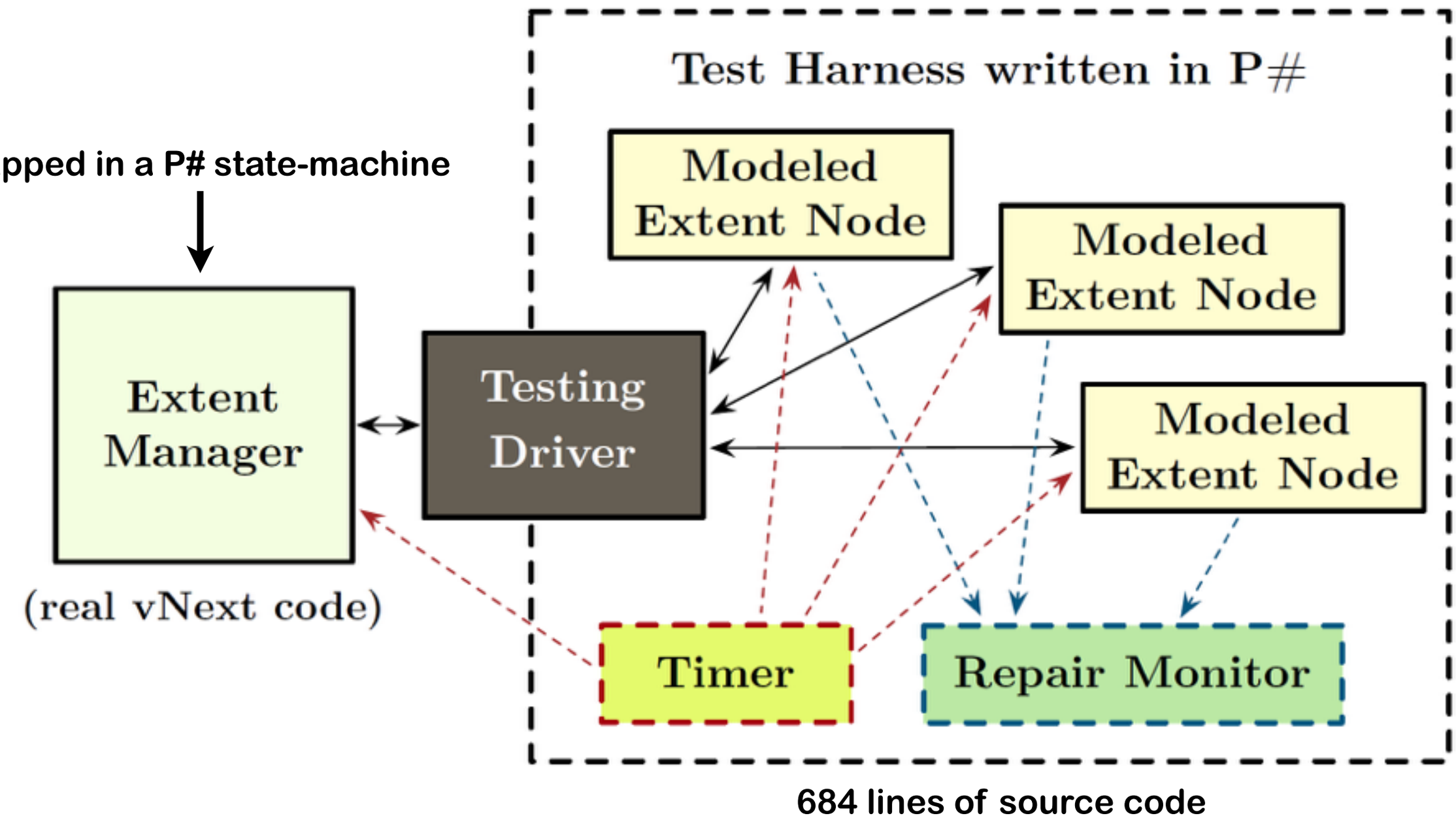
Testing vNext with P#

- P# [PLDI'15] is a systematic testing framework
- Controls and systematically explores all declared sources of nondeterminism in a distributed system
- Support for modeling system components as communicating state-machines to perform component-wise testing (which can scale better than testing unmodified systems)
  - Provides a send primitive for sending messages between P# machines instead of real network, and can systematically explores interleavings
  - Write test harness that injects failures, timeouts, client requests, etc
  - Write safety and liveness specifications
- Can be applied on message passing systems written in .NET or C++
- Open source in GitHub, available for anyone to use!

Bug Finding as a Search Problem

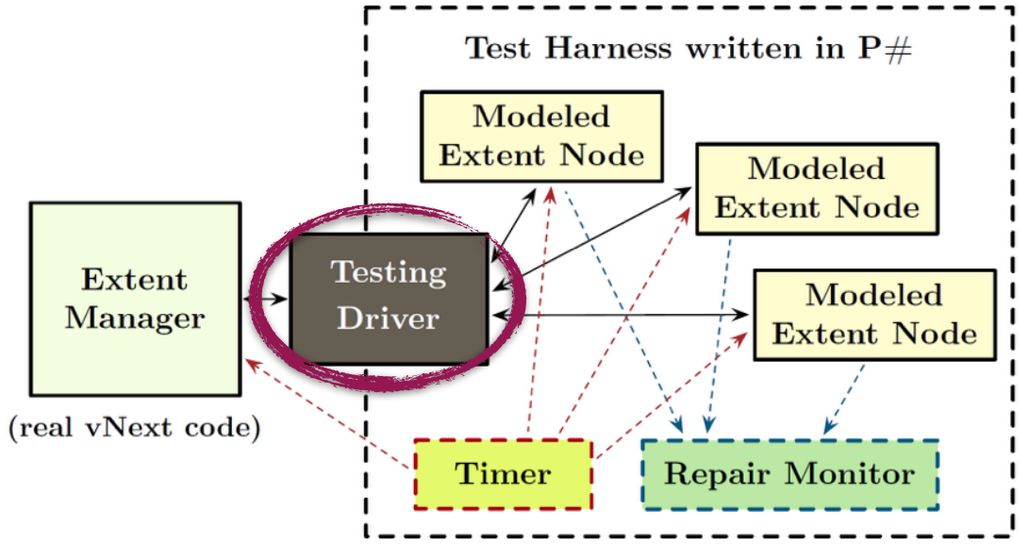


P# test harness for vNext



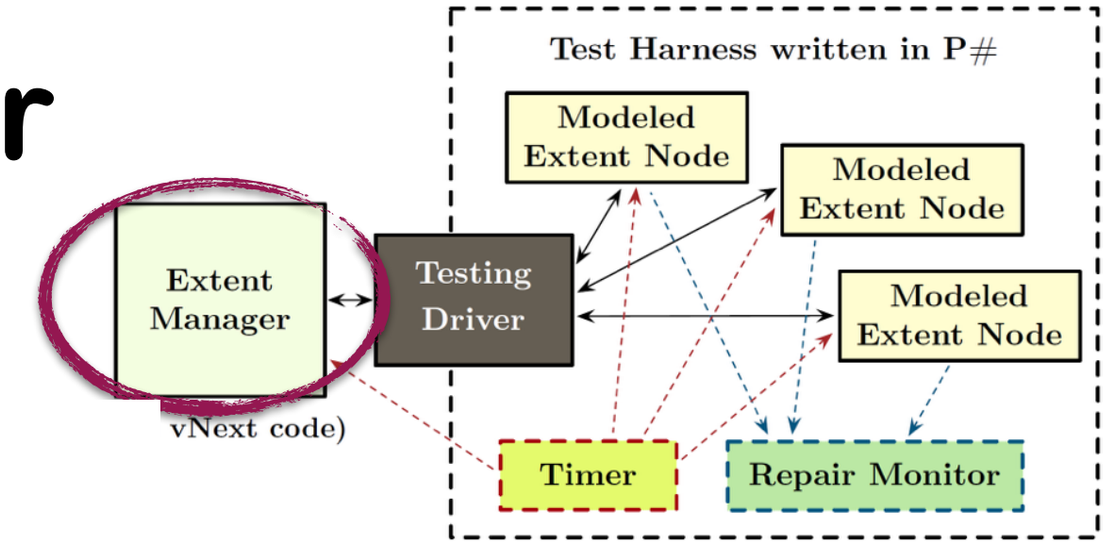
684 lines of source code

Testing Driver



- Setting up the "distributed" system
  - P# simulates system in a single process!
  - Messages go through P#, not the real network!
  - 1 real Extent Manager, 3 modeled ENs and a single extent
  - Small setup sufficient to expose bug → easy to troubleshoot
- Non-determinism modeled in P#
  - E.g. EN failures, timeouts, etc
  - Messages: delays and losses
- Two testing scenarios
  - Scenario I: pass single extent to one EN — assert (extent eventually replicated to the other ENs)
  - Scenario II: fail arbitrary EN and launch a new one — assert (extent eventually replicated to the new EN, target is 3 replicas available)

Real Extent Manager Wrapper Machine



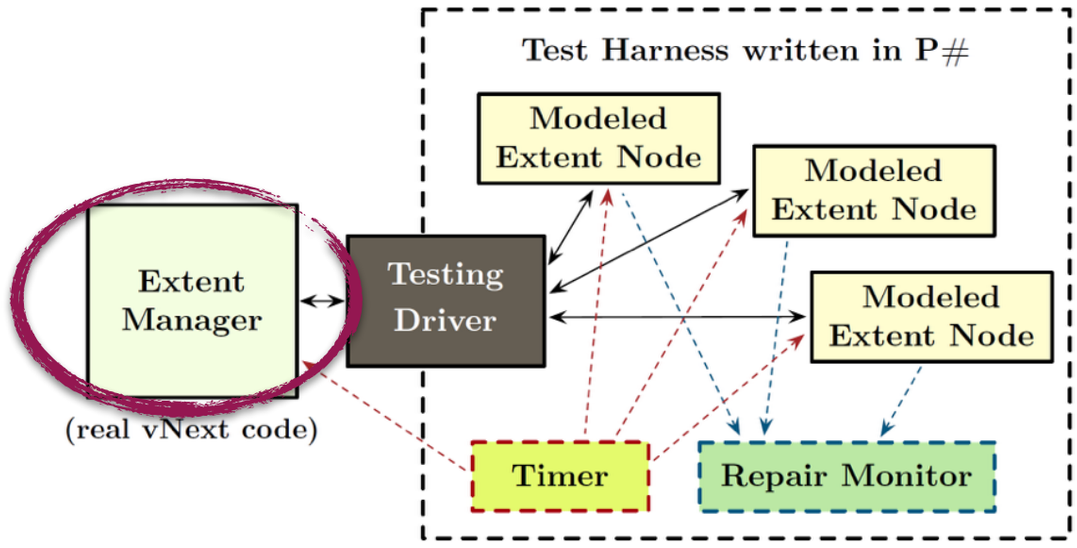

```
// wrapping the target vNext component in a P# machine
class ExtentManagerMachine : Machine {
 private ExtentManager ExtMgr; // real vNext code

 void Init() {
  ExtMgr = new ExtentManager();
  ExtMgr.NetEngine = new MockedNetEngine(); // mock network
  ExtMgr.IsMockingTimer = true; // disable internal timer
 }

 [OnEvent(ExtentNodeMessageEvent, DeliverMessage)]
 void DeliverMessage(ExtentNodeMessage msg) {
   // relay messages from Extent Node to Extent Manager
   ExtMgr.ProcessMessage(msg);
 }

 [OnEvent(TimerTickEvent, ProcessExtentRepair)]
 void ProcessExtentRepair() {
   // extent repair loop driven by external timer
   ExtMgr.ProcessEvent(new ExtentRepairEvent());
 }
}
```

wrap testing target (real Extent Manager)

instantiate testing target and create mock network for outbound messages

relay inbound messages from ENs to the real Extent Manager

Outbound Messages



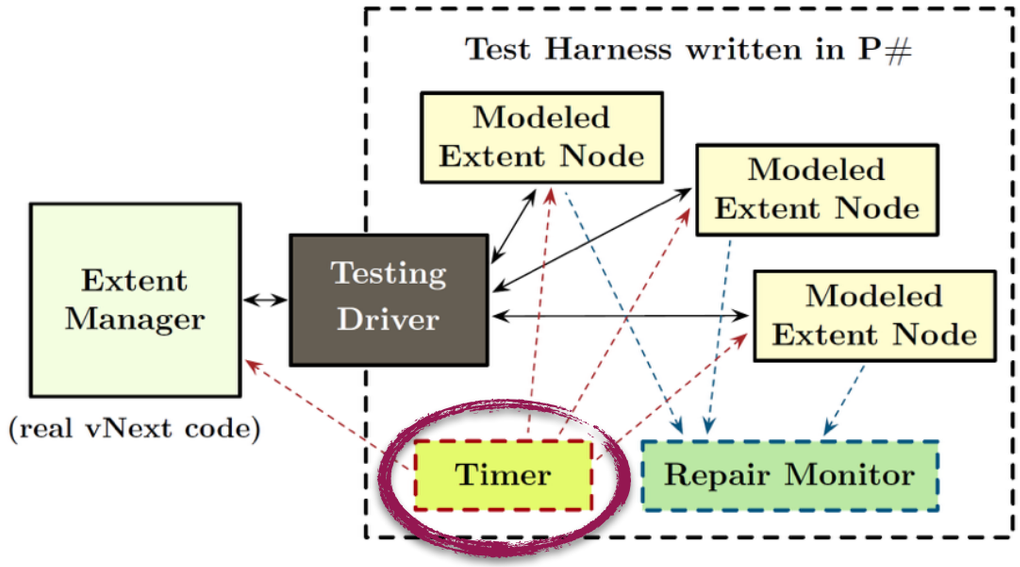

```
// network interface in vNext
class NetworkEngine {
  public virtual void SendMessage(Socket s, Message msg);
}
```

real network engine

```
// mocked engine for intercepting Extent Manager messages
class MockedNetEngine : NetworkEngine {
  public override void SendMessage(Socket s, Message msg) {
    // intercept and relay Extent Manager messages
    PSharpRuntime.Send(this.TestingDriver,
      new MessageFromExtentManagerEvent(), s, msg);
  }
}
```

mocked network engine: intercept and relay outbound messages to P#

Real Extent Manager Driven by P# Timer

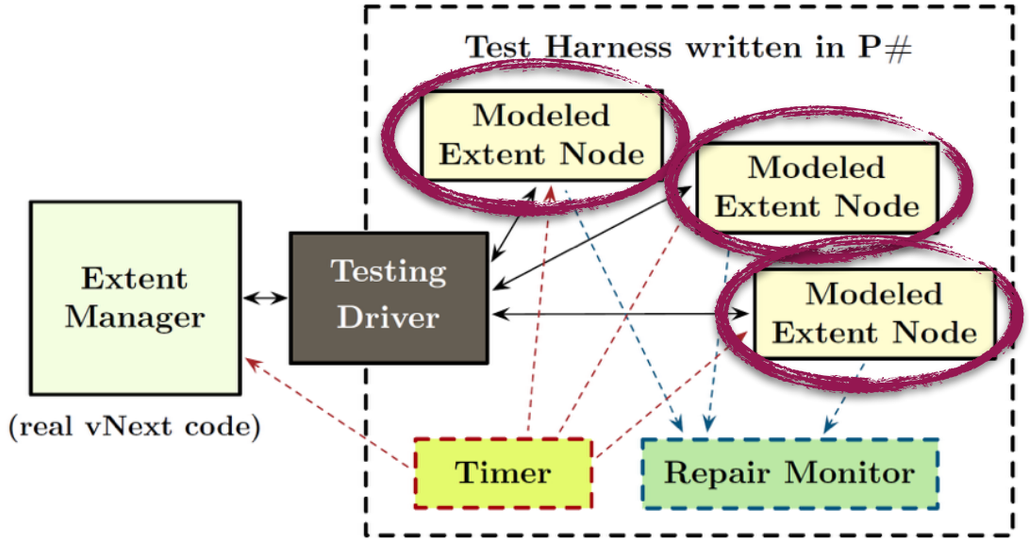



```
// wrapping the target vNext component in a P# machine
class ExtentManagerMachine : Machine {
  private ExtentManager ExtMgr; // real vNext code

  void Init() {
    ExtMgr = new ExtentManager();
    ExtMgr.NetEngine = new MockedNetEngine(); // mock network
    ExtMgr.IsMockingTimer = true; // disable internal timer
  }

  [OnEvent(ExtentNodeMessageEvent, DeliverMessage)]
  void DeliverMessage(ExtentNodeMessage msg) {
    // relay messages from Extent Node to Extent Manager
    ExtMgr.ProcessMessage(msg);
  }

  [OnEvent(TimerTickEvent, ProcessExtentRepair)]
  void ProcessExtentRepair() {
    // extent repair loop driven by external timer
    ExtMgr.ProcessEvent(new ExtentRepairEvent());
  }
}
```

disable internal timer

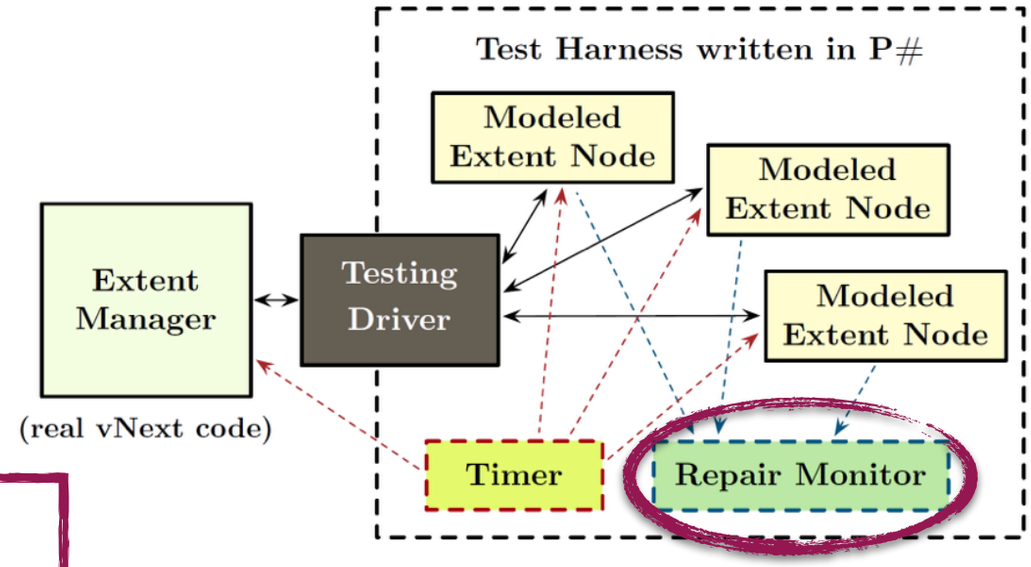
act upon P# timer

Modeled EN Components



- Simplified EN logic only related to the replication process
- Helps to achieve better testing scalability by not having to go through the real ENs
- Reuses EN internal components whenever appropriate (to maximize code reuse)

Liveness Monitor




```
class RepairMonitor : Monitor {
  private HashSet<Machine> ExtentNodesWithReplica;

  // cold state: repaired
  cold state Repaired {
    [OnEvent(ENFailedEvent, ProcessENFailure)]
    void ProcessENFailure(ExtentNodeMachine en) {
        ExtentNodesWithReplica.Remove(en);
        if (ReplicaCount < Harness.REPLICA_COUNT_TARGET)
          jumpto Repairing;
    }
  }

  // hot state: repairing
  hot state Repairing {
    [OnEvent(ExtentRepairedEvent, ProcessRepairCompletion)]
    void ProcessRepairCompletion(ExtentNodeMachine en) {
      ExtentNodesWithReplica.Add(en);
      if (ReplicaCount == Harness.REPLICA_COUNT_TARGET)
        jumpto Repaired;
    }
  }
}
```

cold state:
liveness property satisfied

hot state:
liveness property not satisfied yet

Stuck in hot state infinitely long → liveness bug

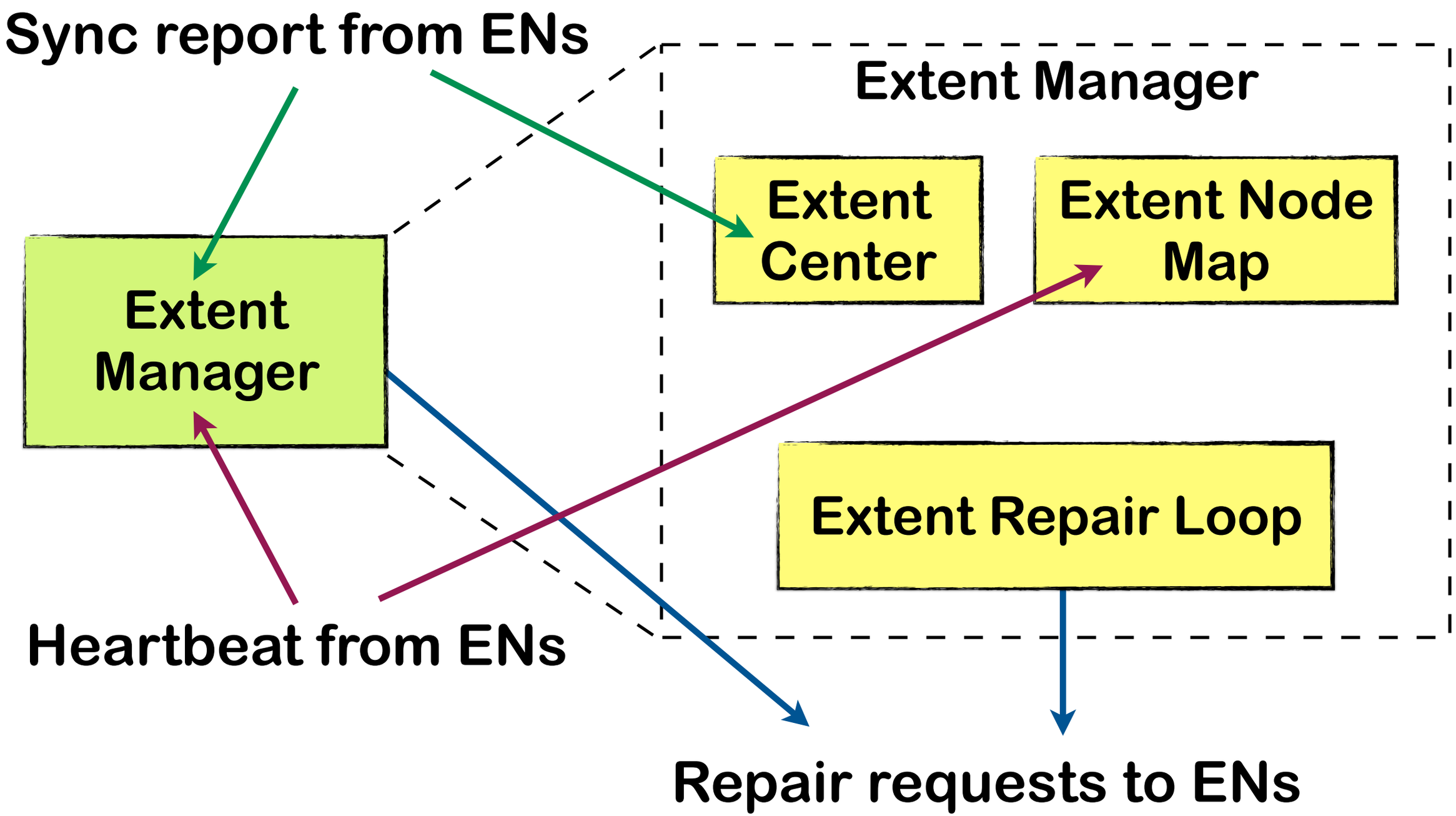
Liveness Checking in P#

- Approach I — similar to MaceMC [NSDI'07]
  - Run until a given large bound
  - Check liveness monitor when bound is reached
  - If in hot state, report potential liveness bug
- Approach II (work-in-progress)
  - Try to detect a fair, infinite loop (lasso-based approach)
  - If the monitor is stuck in a hot state in the loop (i.e. never goes to a cold state), we report a liveness bug

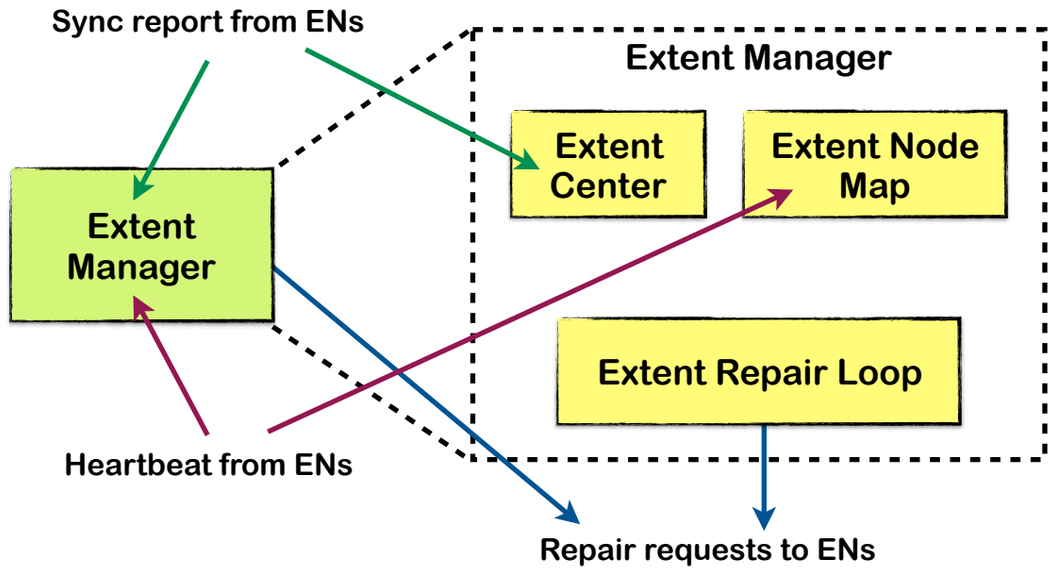
Testing vNext with P#

- Developers spent 2 weeks modeling the environment of the Extent Manager and writing the liveness specification P# monitor (684 loc)
- P# found a liveness violation in a matter of minutes and produced a small sequential trace
- Identify and fix bug by developers in less than an hour (one line of code — see next slide)
- After the fix, developers run the P# test harness for 1 hour without finding any bugs

Extent Manager



Liveness Bug



- Extent Node EN_0 failed (from 3 available)
  - EN_0 removed from ExtentNodeMap
  - Deleted EN_0's extent from ExtentCenter

    (extent { EN_0, EN_1, EN_2 }) → (extent { EN_1, EN_2 })
- Extent Manager received delayed sync report from EN_0
  - Updated ExtentCenter

    (extent { EN_1, EN_2 }) → (extent { EN_0, EN_1, EN_2 })
- EN_0 no longer in ExtentNodeMap → never deleted again from ExtentCenter
- Extent Manager never schedules repair process again

  (extent { EN_1, EN_2 }) → (extent { EN_0, EN_1, EN_2 }) → all healthy!
- If this happens two more times → all replicas lost → customer data lost!
- One line fix: refresh ExtentNodeMap upon sync report!

Read our paper!

Other case studies in Microsoft

- Tools for Software Engineers (TSE) team: used P# during development of a Live Table Migration protocol for Azure (found and fixed >10 safety bugs)

- Team in MSR India: created P# executable model of Azure Service Fabric runtime, which can be eventually used to test arbitrary customer services built on top of the Service Fabric APIs

Thanks! Questions?

P# has been successfully used by Microsoft Azure to test multiple distributed systems.

P# is freely available in GitHub so you can use it for your own projects!

https://github.com/p-org/PSharp

p.deligiannis@imperial.ac.uk