Storage Systems are Distributed Systems (So Verify Them That Way!)

OSDI 2020

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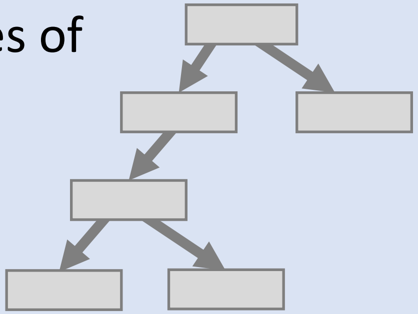
What is Verification?

- Mathematical proof that a program is **correct**.
- Proof is checked by a computer (the **verifier**).

Key-value dictionary implementation

- Complex data structure
- Handle edge cases
- 100s or 1000s of lines of code



Key-value dictionary specification

- Stated simply and mathematically

```
f : Key ⟶ Value

Put(k: Key, v: Value):
  f := f[k ↦ v]

Get(k: Key):
  return f(k)
```

Verifying Persistent Disk Storage Systems

Persistent key-value store implementation

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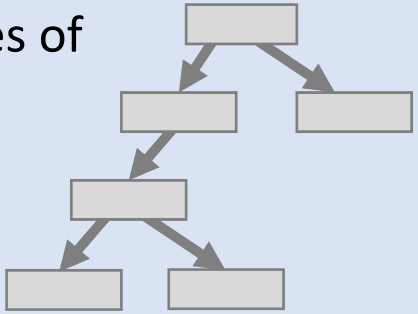

- Handle asynchronous disk access
- IO-efficient data structure
- Caching (eviction policy, etc.)
- Crash safety
- CPU-efficiency

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- Expose a way for user to confirm data has been persisted
- Data persistence on crash

Contributions

- VeriBεtrKV: a complex, verified storage system
  - Crash-safe key-value store based on the **B^{ε}-tree**, an established, state-of-the-art, IO-efficient, write-optimized data structure
  - Written in **Dafny** (compiled via C++)
- **General methodology** for verifying asynchronous systems
- **Linear types** combined with Dafny's dynamic frames to improve the experience of verifying efficient, imperative code

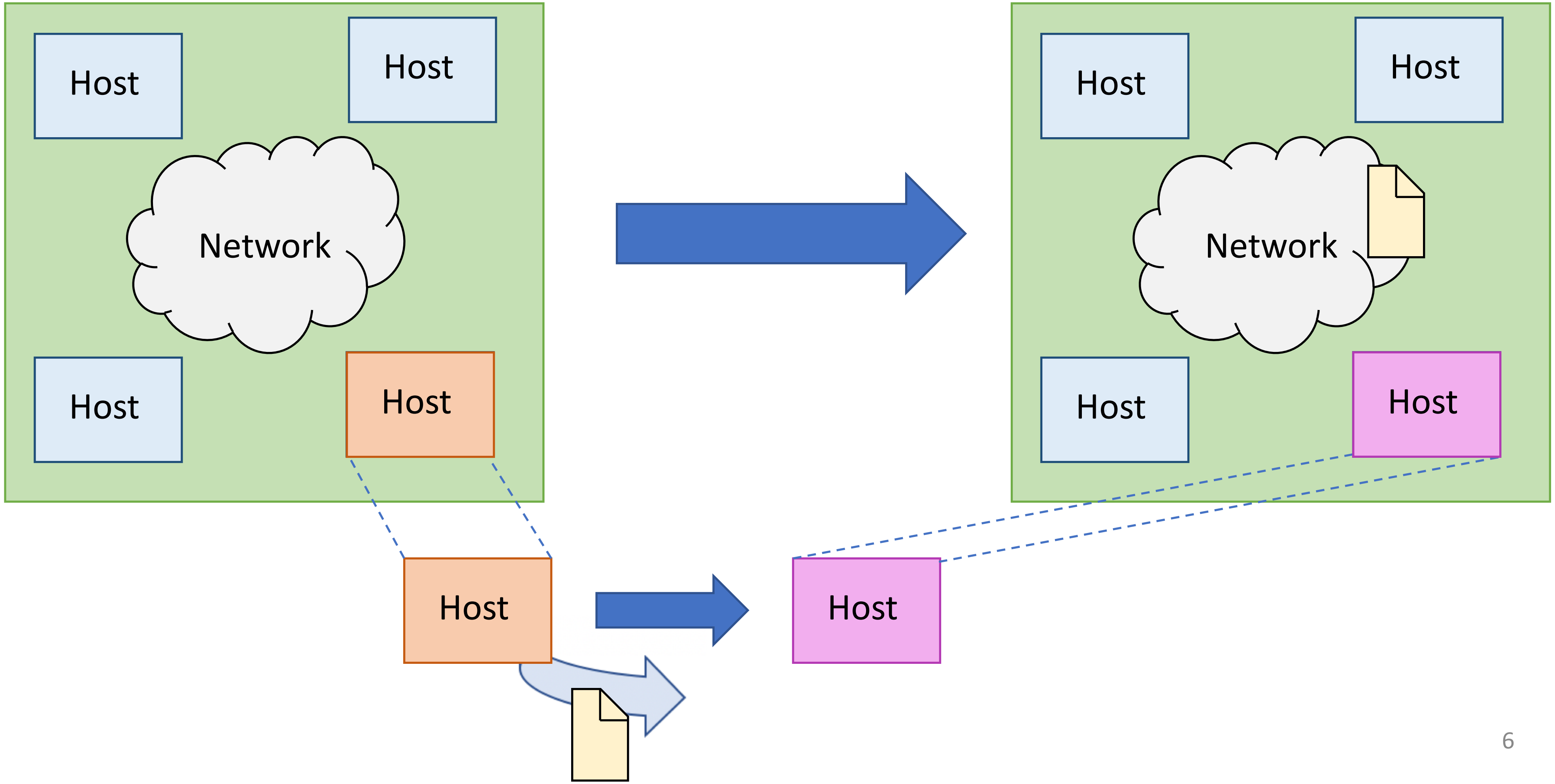
Modeling Disk Systems

- We need a clean & flexible way to encode environmental assumptions.
  - How does the disk work?
  - Assumptions about asynchronicity?
  - What failure scenarios are considered?
- Observation: General problem across asynchronous systems
  - **IronFleet** (2015) uses **state machines** to model networked distributed systems.
  - We generalize and apply to storage systems.
  - No need for a domain-specific logic!

Modeling Asynchronous Systems

Network system state machine

Host state machine

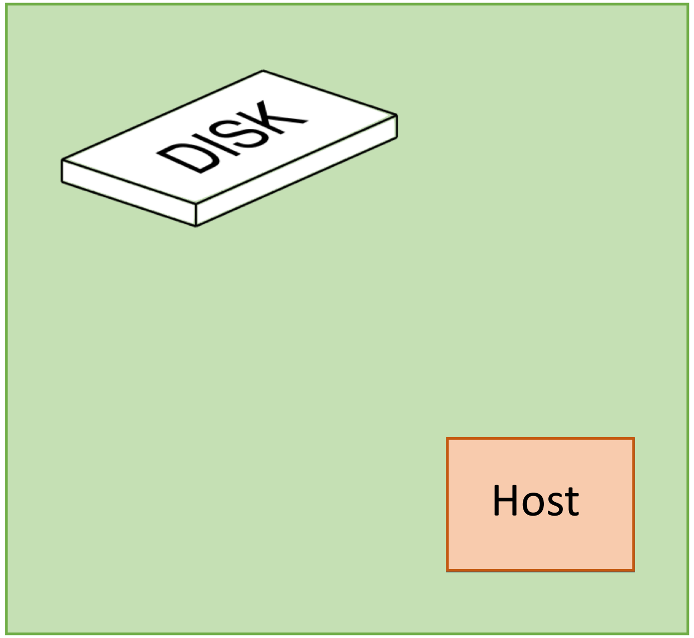


Modeling Asynchronous Systems

- Templated state machine **NetworkSystem<Host>** is defined in terms of **Host** state machine.
- This state machine definition **encodes all environmental assumptions!**
  - Packet delivery
  - Packet reordering
  - Packet duplication
- We demonstrate that we can use this approach for other asynchronous systems, like our disk system.

Modeling disk systems

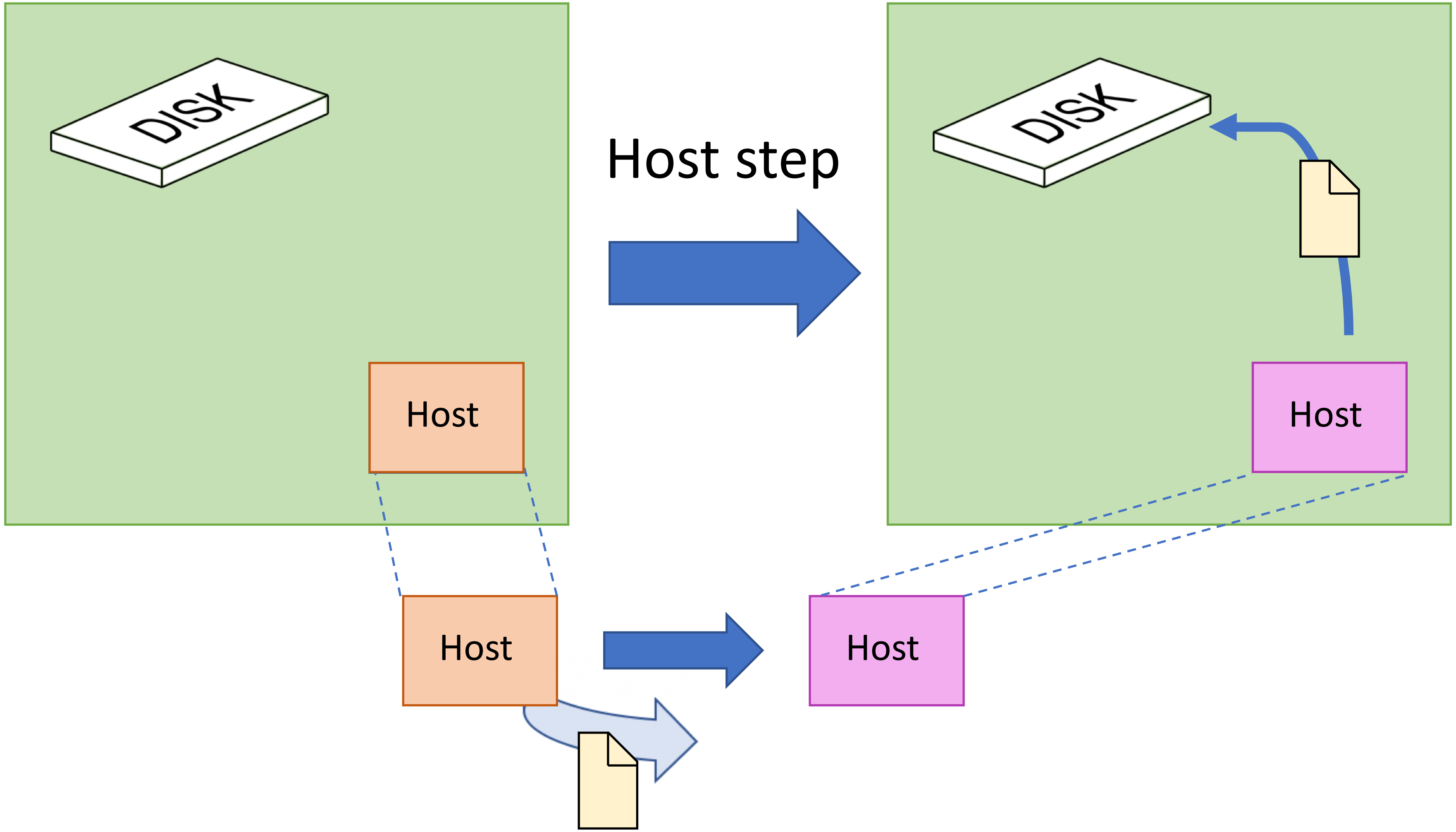
DiskSystem<Host>



Modeling disk systems

DiskSystem<Host>

Host



Modeling disk systems

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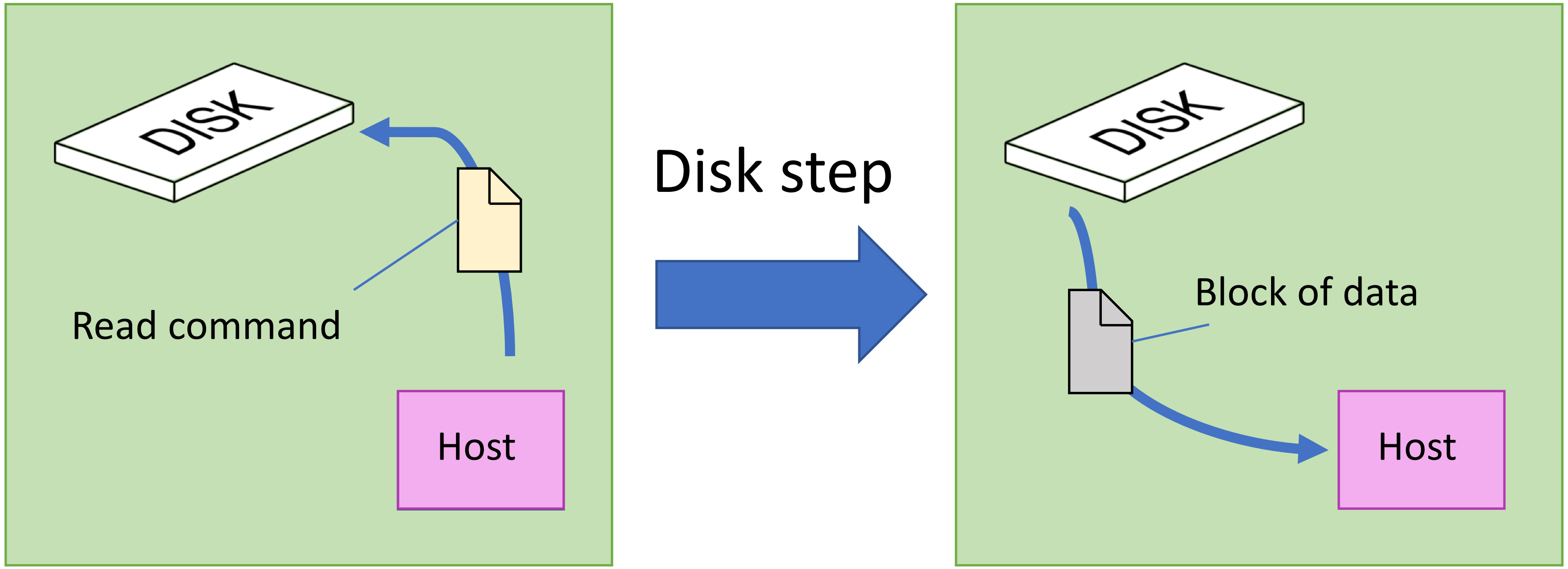

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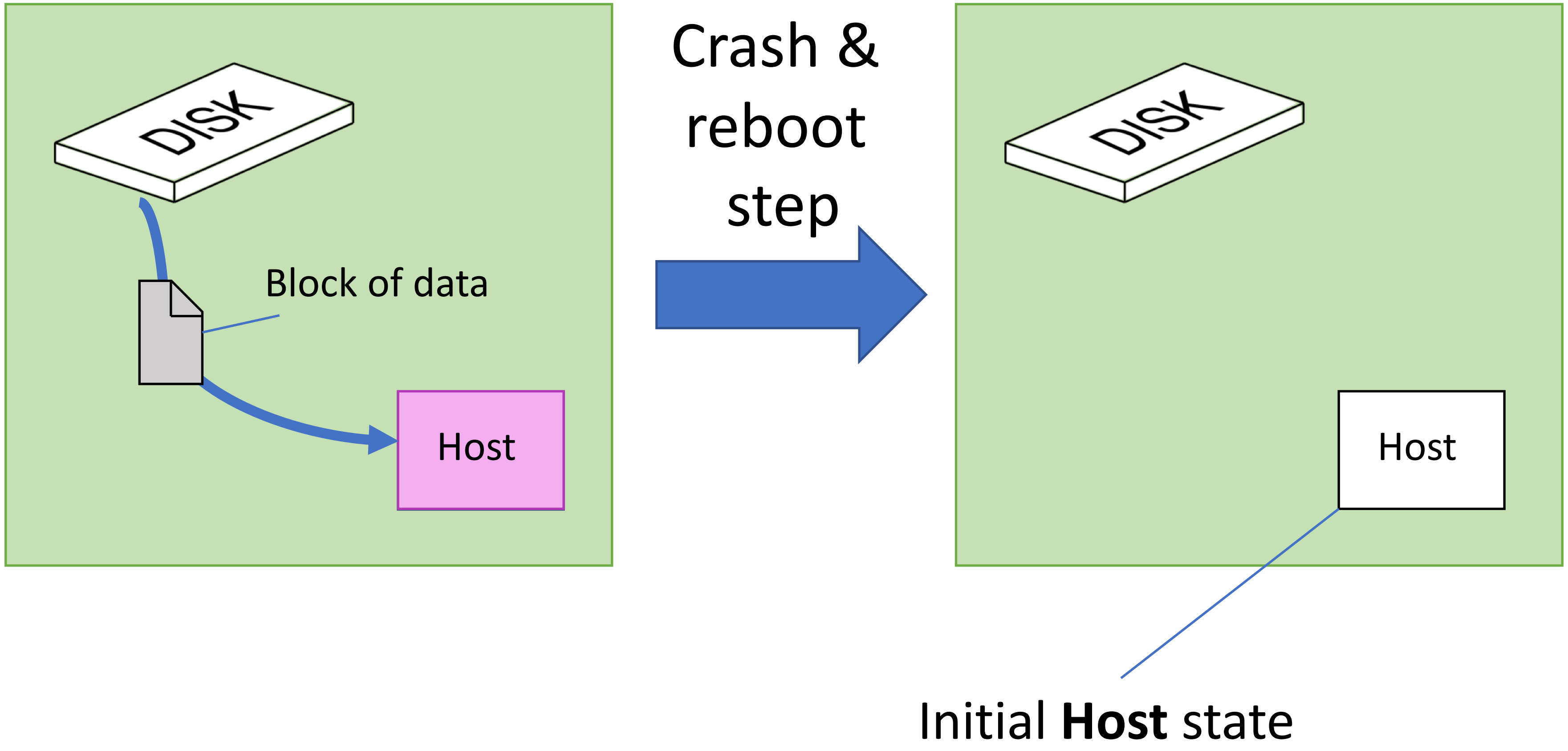
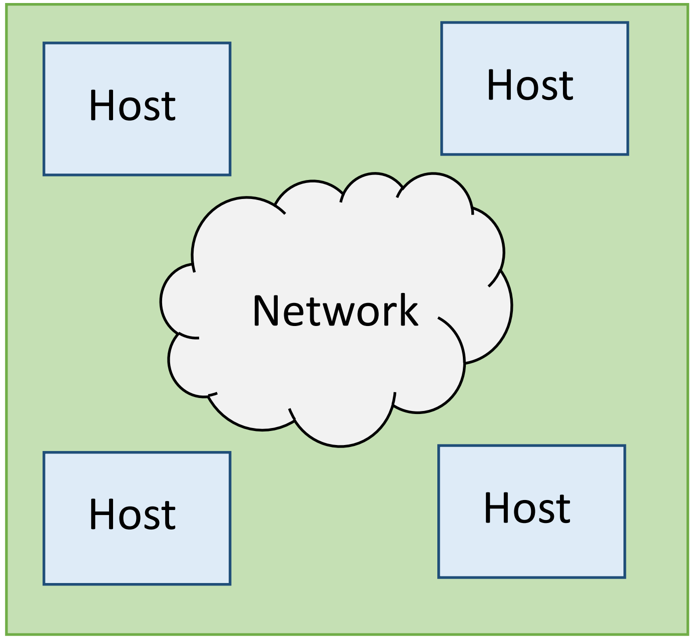
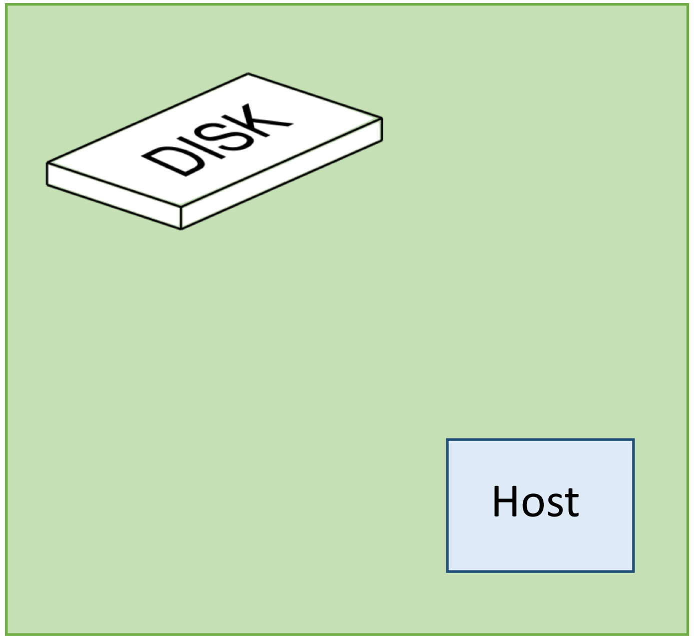


NetworkSystem<Host>



- Network delivering packets
- Packet reordering
- Packet duplication

DiskSystem<Host>



- Disk
- IO queue
- Command reordering
- Host failure
- Host **reinitialization**
- (Limited) spontaneous data corruption

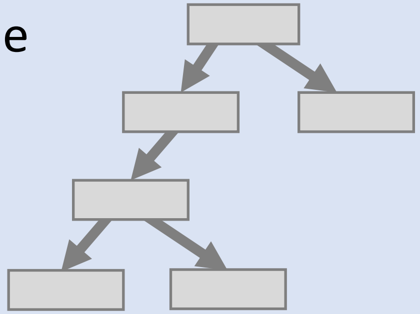
Modeling Disk Systems

- Method: encode **any** environmental assumptions in the definition of templated state machine **System<Host>**
- Natural extension of IronFleet's method
- Clean split between environmental assumptions (**System**) and implementation details (**Host**)
- Environmental assumptions easy to read and understand

Verifying Persistent Disk Storage Systems

Persistent key-value store implementation

- Complex data structure
- Handle edge cases
- 1000s of lines of code



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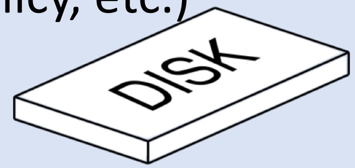

Persistent key-value store specification

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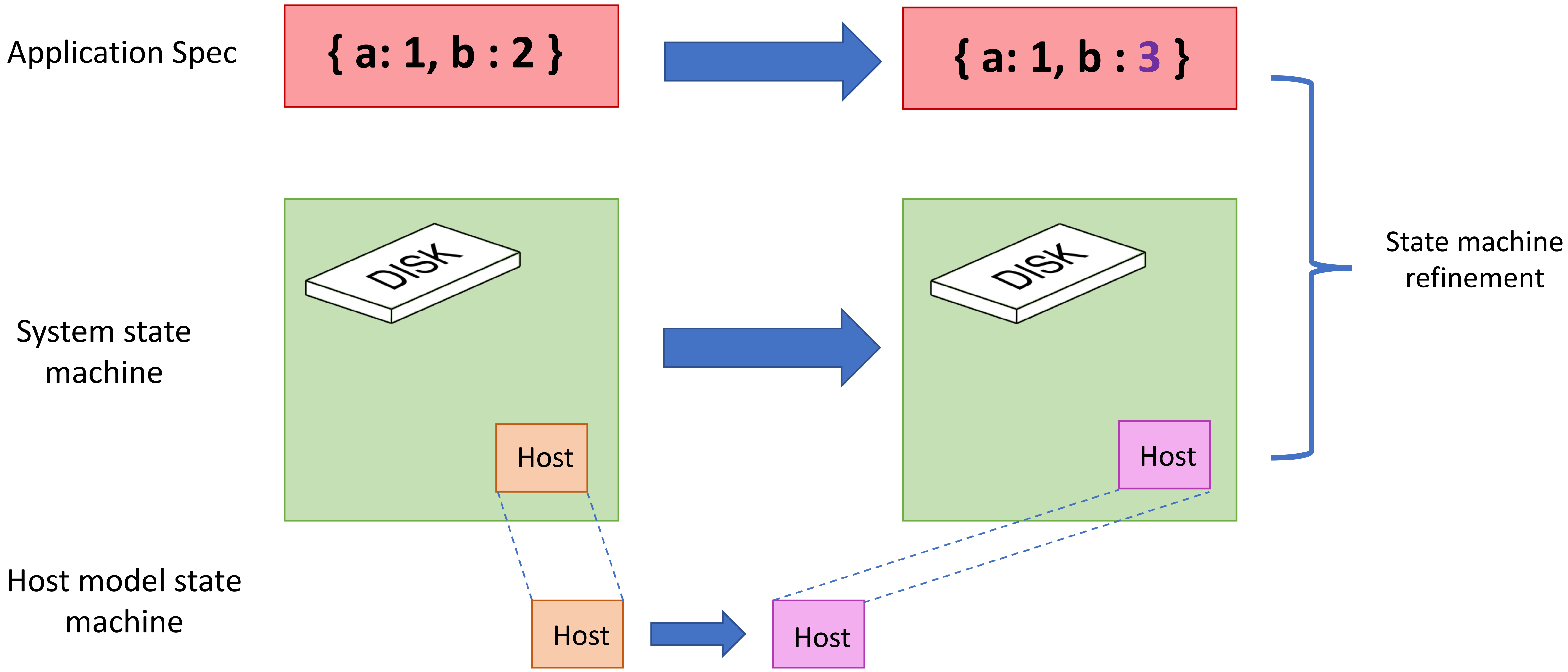

Application Spec
{ a: 1, b : 2 }
{ a: 1, b : 3 }
System state machine
DISK
Host
DISK
Host
State machine refinement
Host model state machine
Host
Host

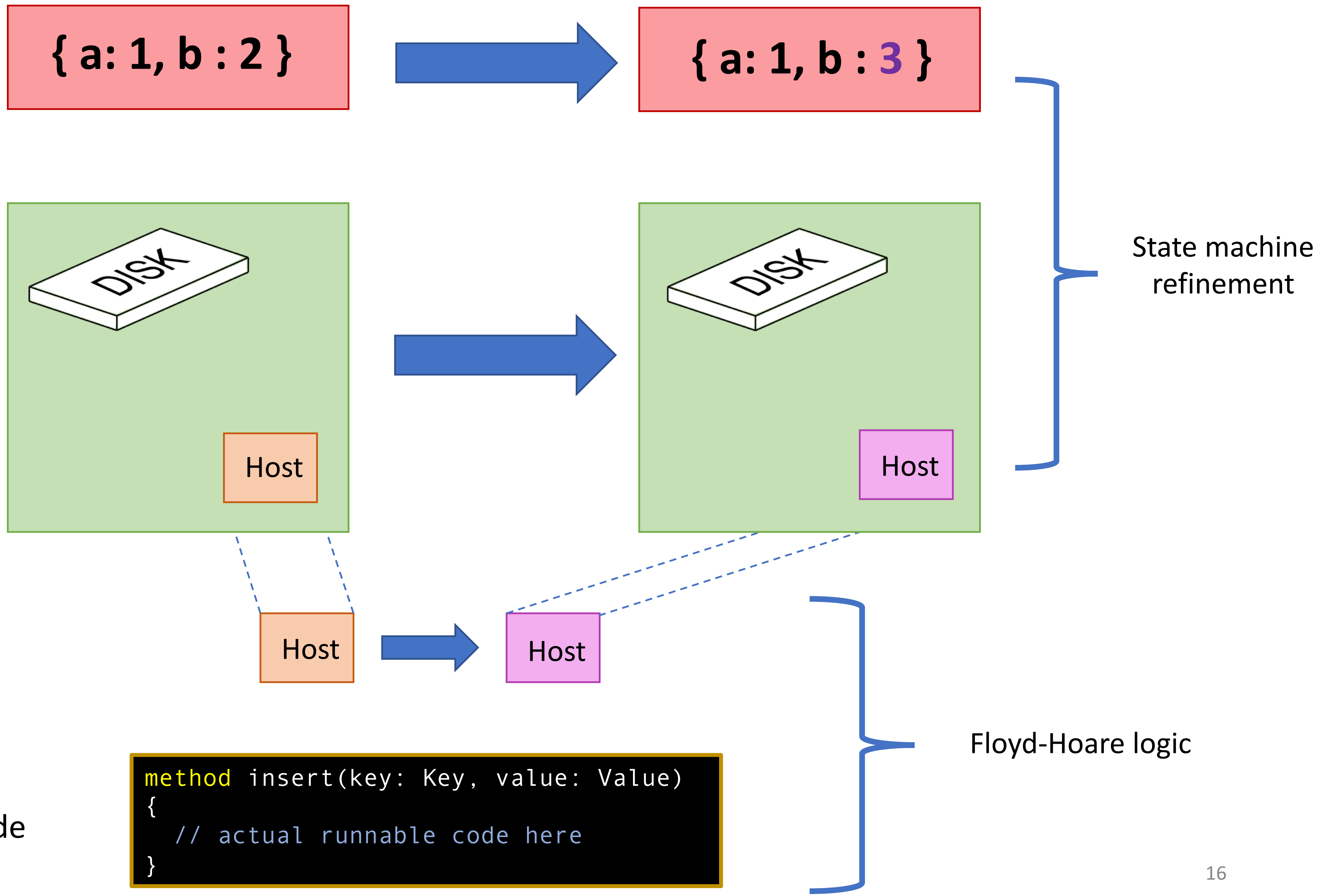
Application Spec

System state machine

Host model state machine

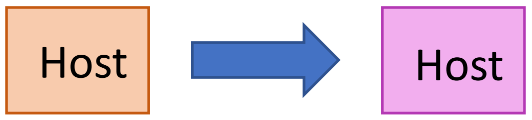
- Bε-tree operations
- Caching logic
- Journal logic

Implementation code



Writing Efficient, Verified Code

Host model state machine
- B^{ε}-tree operations
- Caching logic
- Journal logic



Implementation code

```
method insert(key: Key, value: Value)
{
  // actual runnable code here
}
```

Floyd-Hoare logic

- Goal: efficient, runnable code that implements this state machine.
  - Imperative code with mutable update-in-place data structures

Memory Aliasing

- Dafny uses a memory-reasoning strategy called **dynamic frames**.
  - This strategy requires explicit aliasing information.

```
class Point {
  var x: int;
  var y: int;
}

method foo(a: Point, b: Point)
modifies a, b
requires a != b
{
  a.x := 1;
  b.x := b.x - 1;

  assert a.x == 1;
}
```

```
method main()
{
  var a := new Point();
  foo(a, a);
}
```

Memory Aliasing

- Manually adding aliasing conditions is cumbersome.
  - Number of pairwise conditions grows quadratically.
  - Handling deep data structures requires reasoning about sets of objects.

```
predicate ReprInv()
reads this, persistentIndirectionTable, ephemeralIndirectionTable,
    frozenIndirectionTable, lru, cache, blockAllocator
    Repr()

& persistentIndirectionTable.Repr !! ephemeralIndirectionTable.Repr
tionTable.Repr
ionTable.Repr
pr
ndirectionTable.Repr)
}
```

```
static predicate {:opaque} ReprSeqDisjoint(buckets: seq<MutBucket>)
reads set i | 0 <= i < |buckets| :: buckets[i]
{
  forall i, j
      buckets[
}
```

```
twostate lemma SplitChildOfIndexPreservesWFShape(node: Node, childidx: int)
// ...
requires unchanged(old(node.repr) - {node, node.contents.pivots, node.contents.children,
node.contents.children[childidx]})
// ...
requires node.contents.children[childidx].repr <= old(node.contents.children[childidx].repr)
// ...
requires fresh(node.contents.children[childidx+1].repr - old(node.contents.children[childidx].repr))
requires node.contents.children[childidx+1].height == old(node.contents.children[childidx].height)
requires DisjointSubtrees(node.contents, childidx, (childidx + 1))
requires node.repr == old(node.repr) + node.contents.children[childidx+1].repr
ensures WFShape(node)
```

Memory Aliasing

- We could just write immutable code instead …

```
datatype Point(x: int, y: int)

method foo(
    a: Point,
    b: Point)
returns (a': Point, b': Point)
{
  a' := a.(x := 1);
  b' := b.(x := b.x - 1);

  assert a'.x == 1;
}
```

- This makes verification much easier.
- But copying objects is slower, especially large sequences.

Faster Code with Linear Types

- What if we could:
  - Verify objects as if they were immutable,
  - But have the compiler generate code with in-place updates?
- Use a **linear type system** to enforce exclusive ownership of objects.

Faster Code with Linear Types

```
datatype Point(x: int, y: int)

method foo(
    linear a: Point,
    linear b: Point)
returns (linear a': Point,
         linear b': Point)
{
  a' := a.(x := 1);
  b' := b.(x := b.x - 1);

  assert a'.x == 1;
}
```

```
method main()
{
  linear var a := Point(0, 0);
  foo(a, a);
}
```

Adding Linear Types to Dafny

- Aliasing errors are now immediate type errors.
- Inspired by prior verification work, Cogent (2016)
- Production languages like Rust also demonstrate that linear semantics are feasible for a lot of systems code.
- When linearity is too constraining, we can still fall back to dynamic frames and theorem-proving.
  - Enables code not expressible in a strict linear type system
  - Used in key places in VeriBεtrKV

VeriBεtrKV Implementation

- Code is compiled via a C++ backend for Dafny

Component	Lines of code	Total	
Environment model	450	730	Trusted
Application spec	280		
Executable code	6,500	6,500	Impl
Host model	2,800	47,800	Proof
Refinement Proof	23,000		
Floyd-Hoare Proof	22,000		

Trusted Compute Base (TCB)
Environment model
Application spec
Kernel API to disk reads/writes
Dafny toolchain
C++ toolchain

- Proof : code ratio is ~ 7, comparable to IronFleet.
- System is ~ 3x as large as IronFleet.

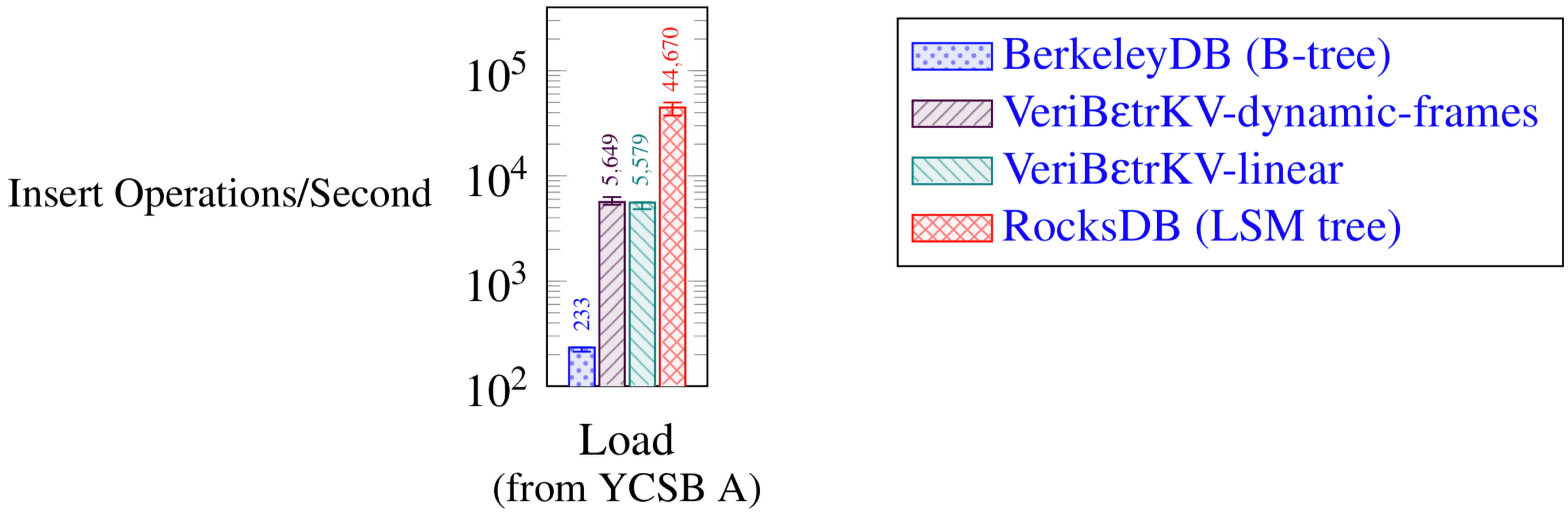
Development Process

- Linear types improve both **proof length** and **verification times.**

Component	LoC (dynamic frames)	LoC (linear)	Reduction
In-memory hash table	1967	1352	**31%**
In-memory search tree	2509	1904	**24%**

- Maximum method-level interactive verification time dropped 42s → 32s
- 99th percentile dropped 6.1s → 4.8s
- Linear type errors are instant!

Performance Benchmarks



10 million insertion operations, 2GiB RAM, single-threaded

Performance Benchmarks

- VeriBεtrKV's B^{ε}-trees beats B-trees on inserts, as expected.
- VeriBεtrKV is still behind RocksDB, one of the fastest, highly-tuned unverified key-value stores.
- VeriBεtrKV lags *both* BerkeleyDB and RocksDB on queries
  - Memory fragmentation results in smaller effective cache size
  - Missing optimizations needed to match query performance of B-trees

Conclusion

- Defining **System<Host>** state machines is a convenient and flexible way to encode environmental assumptions for system verification.
- Linear type systems are practical for systems code and relieve both developer and verifier burden.
- VeriBεtrKV advances towards performance of state-of-the-art non-verified systems, with much stronger guarantees.

- Thank you
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