

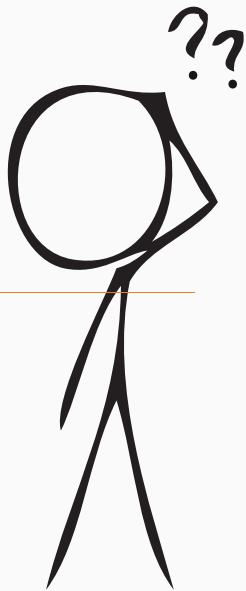
# VERIFICATION OF CONCURRENT AND DISTRIBUTED SYSTEMS

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Nickolai Novik

April 26, 2018

<http://github.com/jettify>



# ABOUT ME

- **[Software Engineer]** DataRobot
- **[Github]** <http://github.com/jettify>
- **[Twitter]** <https://twitter.com/isinf>
- **[aio-lib]** <https://github.com/aio-lib>
- **[Projects]** *aiomonitor, aiohttp-debugtoolbar, aiobotocore, aiomysql, aiiodbc, aiohttp-admin, aiowlock, aiozipkin, etc*

## How many of you heard of formal methods?

- I used one on of: Coq, Isable, TLA+, Alloy, Spin.
- I heard about it, but never used.
- I think formal methods are kinda cool.

# **PROBLEM STATEMENT. MOTIVATIONAL EXAMPLE**

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# CONCURRENT AND DISTRIBUTED SYSTEMS ARE HARD

**Most of industry uses following techniques for quality assurance:**

- Design review
- Code review
- Unit/Integration/Functional testing
- Static code analysis
- Code coverage
- Stress testing
- Fault-injection testing [1]

# DISTRIBUTED ALGORITHMS EXTREMELY HARD

## Chord: A Scalable Peer-to-peer Lookup Protocol for Internet Applications

Ion Stoica<sup>†</sup>, Robert Morris<sup>‡</sup>, David Liben-Nowell<sup>‡</sup>, David R. Karger<sup>‡</sup>, M. Frans Kaashoek<sup>‡</sup>, Frank Dabek<sup>‡</sup>, Hari Balakrishnan<sup>‡</sup>

### Abstract—

A fundamental problem that confronts peer-to-peer applications is the efficient location of the node that stores a desired data item. This paper presents *Chord*, a distributed lookup protocol that addresses this problem. *Chord* provides support for just one operation: given a key, it maps the key onto a node. Data location can be easily implemented on top of *Chord* by associating a key with each data item, and storing the key/data pair at the node to which the key maps. *Chord* adapts efficiently as nodes join and leave the system, and can answer queries even if the system is continuously changing. Results from theoretical analysis and simulations show that *Chord* is scalable: communication cost and the state maintained by each node scale logarithmically with the number of *Chord* nodes.

tem.

A *Chord* node requires information about  $O(\log N)$  other nodes for *efficient* routing, but performance degrades gracefully when that information is out of date. This is important in practice because nodes will join and leave arbitrarily, and consistency of even  $O(\log N)$  state may be hard to maintain. Only one piece of information per node need be correct in order for *Chord* to guarantee correct (though possibly slow) routing of queries; *Chord* has a simple algorithm for maintaining this information in a dynamic environment.

## Chord

is popular algorithm for P2P systems, paper published in 2001 by strong team of MIT researchers, 10 years later bug found in specification [11, 12]. Paper won best paper award.

# SOMETIMES COST OF ERROR IS VERY HIGH 2



## Therac-25

radiation therapy machine, because of concurrent programming errors, it sometimes gave its patients radiation doses that were hundreds of times greater than normal [2]

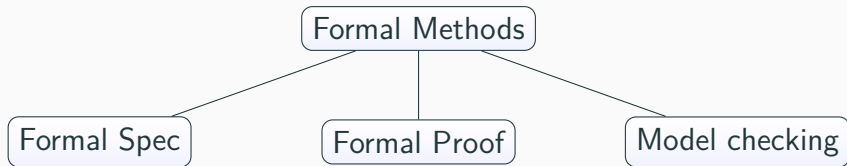
# FORMAL METHODS

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# FORMAL METHODS

**Formal Methods** - are a particular kind of mathematically based techniques for the specification, development and verification of software systems [8].

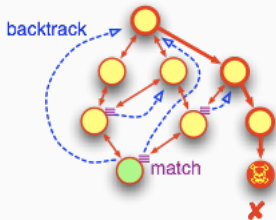


# MODEL CHECKING

**Model checking** is a technique for automatically verifying correctness properties of finite-state systems.

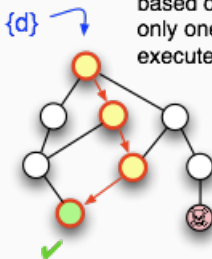
model checking:

all program state are explored  
until none left or defect found

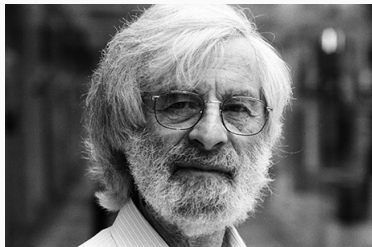


testing:

based on input set  $\{d\}$   
only one **path**  
executed at a time



# TLA+ – TEMPORAL LOGIC OF ACTIONS



**TLA+** language developed by **Leslie Lamport**. It is used to design, model, document, and verify concurrent systems, has been described as exhaustively-testable pseudocode and blueprints for software systems.

# TLA+ DESCRIPTION

**TLA+** is **specifications** language, it is precise written description of what a system suppose to do. **TLA Toolbox** distribution of TLA related tools. **TLC** - model checker tool to validate invariants stated in spec. **TLAPS** - mechanical proof checker.

**Released** April 23, 1999; 18 years ago

**Syntax** math notation, similar to  $\text{\LaTeX}$

**Implem.** Java

**License** MIT

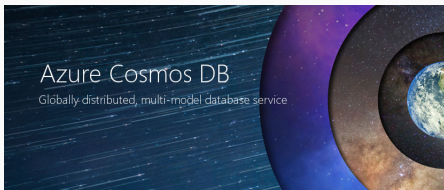
**IDE** TLA Toolbox (Eclipse based) [5]



**TLA+** helped to find design bugs in **S3, Dynamo, EBS, EC2**, etc, some requiring traces of 35 steps. [9]

# TLA+ INDUSTRY USAGE: MICROSOFT

MS used TLA+ to define consistency protocol for CosmosDB and memory allocator for XBox [7]



# TLA+ INDUSTRY USAGE: OPEN-SOURCE

Open source projects use TLA+ to verify algorithms:

- **Linux Kernel** – verify fairness of qspinlock [6]
- **Elastic** – data replication protocol [3]
- **Mongodb** – data replication protocol [13]
- **Hadoop/YARN** – registry of long lived processes [4]



# TLA+ BASICS

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# TLA+ HELLO WORLDS

```
1  ----- MODULE HourClock -----
2  EXTENDS Naturals
3  VARIABLE hr
4  HCini == hr \in (1 .. 12)
5  HCnxt == hr' = IF hr # 12 THEN hr + 1 ELSE 1
6  HC == HCini /\ [] [HCnxt]_hr
7  -----
8  THEOREM HC => []HCini
9  =====
```

```
1  |----- MODULE HourClock -----|
2  | EXTENDS Naturals |
3  | VARIABLE hr |
4  |  $HCini \triangleq hr \in (1 .. 12)$  |
5  |  $HCnxt \triangleq hr' = \text{IF } hr \neq 12 \text{ THEN } hr + 1 \text{ ELSE } 1$  |
6  |  $HC \triangleq HCini \wedge \square [HCnxt]_{hr}$  |
7  |-----|
8  | THEOREM  $HC \Rightarrow \square HCini$  |
9  |-----|
```

# TLA+ SYNTAX. LOGIC

Basic logical operators:

Symb.	ASCII	Python	Description
$\vee$	<code>\/</code>	<code>or</code>	logical OR
$\wedge$	<code>/\</code>	<code>and</code>	logical AND
$\neg$	<code>~</code>	<code>not</code>	logical NOT
<code>=</code>	<code>=</code>	<code>==</code>	boolean operator, checks equality, it is not an assignment operator.
$\triangleq$	<code>==</code>	<code>=</code>	means defined to equal.

## EXERCISE

$$FALSE \wedge (TRUE \wedge (FALSE \vee TRUE) \vee (TRUE \vee FALSE)) = \boxed{??}$$

# EXERCISE

$$\boxed{FALSE} \wedge (TRUE \wedge (FALSE \vee TRUE) \vee (TRUE \vee FALSE)) = \boxed{FALSE}$$

# TLA+ SYNTAX. MORE LOGIC

More logic operators:

Symb.	ASCII	Python	Description
$\exists$	\E	<code>any()</code>	means "there exists"
$\forall$	\A	<code>all()</code>	means "for all"
:	:		reads as "such that"

$\exists x \in 1, 2, 3, 4, 5 : x > 3$  - exists  $x$  in set of integers 1, 2, 3, 4, 5 such that  $x > 3$  expression evaluates to TRUE.

# TLA+ SYNTAX. MORE LOGIC

More logic operators:

Operator	ASCII	Description
$\square$	<code>[]</code>	formula is TRUE on each step
$\Rightarrow$	<code>=&gt;</code>	implication $x\_imp\_y = y$ <b>if</b> $x$ <b>else</b> <b>True</b>
$\square'$	<code>'</code>	reads as prime, state of variable on next step $x' = x + 1$

# TLA+ SYNTAX. SETS

Basic set operations:

Symb.	ASCII	Python	Description
$S \cup T$	<code>\union</code>	<code>s.union(t)</code>	Union
$S \cap T$	<code>\intersect</code>	<code>s.intersection(t)</code>	Intersection
$S \subseteq T$	<code>\supseteq</code>	<code>s in t</code>	Membership
$S \setminus T$	<code>\</code>	<code>s.difference(t)</code>	Difference

# TLA+ SPEC TEMPLATE

```
1  ----- MODULE ModuleName -----
2  (* Imports and variable declarations*)
3  EXTENDS Naturals, Sequences, Integers, FiniteSets
4  -----
5  (* Initial Conditions *)
6  Init == ...
7  TypeOK == ...
8  -----
9  (* Body of the spec *)
10 Next == ...
11 Invariant == ...
12 -----
13 (* Invariant declaration with temporal formula *)
14 THEOREM Spec => ...
15 =====
```

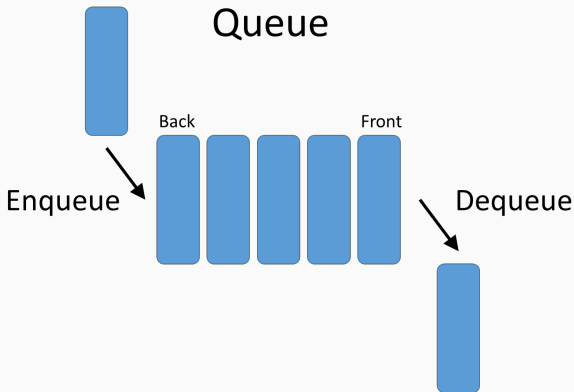


# MULTITHREADING QUEUE SPEC

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# MULTITHREADING QUEUE

Classic *bounded buffer*, attempts to put an element into a full queue or take from empty will block.



# QUEUE IMPLEMENTATION, PART 1

```
1  import threading
2
3  class BoundedQueue:
4      def __init__(self, capacity=3):
5          self.capacity = capacity
6          self.buffer = [None] * capacity
7          self.mutex = threading.Lock()
8          self.condition = threading.Condition(self.mutex)
9          self.size = 0
10         self.head = 0
11         self.tail = 0
12
13     def is_full(self):
14         return self.size == self.capacity
15
16     def is_empty(self):
17         return self.size == 0
18
19     def _next(self, x):
20         return (x + 1) % self.capacity
```

# QUEUE IMPLEMENTATION, PART 2

```
22     def put(self, item):
23         with self.condition:
24             while self.is_full():
25                 self.condition.wait()
26             self.buffer[self.tail] = item
27             self.tail = self._next(self.tail)
28             self.size += 1
29             self.condition.notify()
30
31     def get(self):
32         with self.condition:
33             while self.is_empty():
34                 self.condition.wait()
35             item = self.buffer[self.head]
36             self.buffer[self.head] = None
37             self.head = self._next(self.head)
38             self.size -= 1
39             self.condition.notify()
40             return item
```

# CAN YOU GUESS TYPE OF BUG?



# QUEUE TLA SPEC: PART 1

```
1  ----- MODULE buffer -----
2  EXTENDS Naturals, Sequences
3
4  CONSTANTS Producers,
5             Consumers,
6             BufCapacity,
7             Data
8
9  ASSUME /\ Producers # {}
10         /\ Consumers # {}
11         /\ Producers \intersect Consumers = {}
12         /\ BufCapacity > 0
13         /\ Data # {}
14  VARIABLES buffer,
15             waitSet
16  -----
```

Imports and variables definitions.

# QUEUE TLA SPEC: PART 2

```
16 -----
17 Participants == Producers \union Consumers
18 RunningThreads == Participants \ waitSet
19
20 TypeInv == /\ buffer \in Seq(Data)
21             /\ Len(buffer) \in 0..BufCapacity
22             /\ waitSet \subseq Participants
23
24 Notify == IF waitSet # {}
25           THEN \E x \in waitSet : waitSet' = waitSet \ {x}
26           ELSE UNCHANGED waitSet
27
28 NotifyAll == waitSet' = {}
29
30 Wait(t) == waitSet' = waitSet \union {t}
31 -----
```

Helper formulas.

# QUEUE TLA SPEC: PART 3

```
32 Init == buffer = <<>> /\ waitSet = {}
33 Put(t,m) == IF Len(buffer) < BufCapacity
34             THEN /\ buffer' = Append(buffer, m)
35                  /\ Notify
36             ELSE /\ Wait(t)
37                  /\ UNCHANGED buffer
38 Get(t) == IF Len(buffer) > 0
39             THEN /\ buffer' = Tail(buffer)
40                  /\ Notify
41             ELSE /\ Wait(t)
42                  /\ UNCHANGED buffer
```

Initial conditions and main methods specification.



# QUEUE TLA SPEC: PART 4

```
43  Next == \E t \in RunningThreads : \/ t \in Producers /\ \E m \in Data : Put(t,m
44                                     \/ t \in Consumers /\ Get(t)
45
46  Prog == Init /\ [] [Next]_<<buffer, waitSet>>
47  -----
48  NoDeadlock == [] (RunningThreads # {})
49
50  THEOREM Prog => [] TypeInv /\ NoDeadlock
```

Invariant definition

# QUEUE TRACE

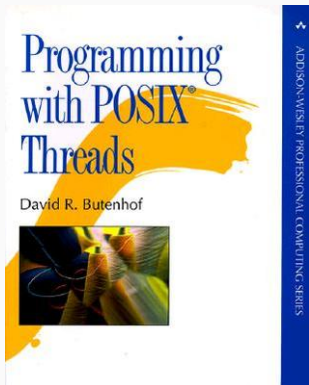
TLC shows all steps that leads to *invariant violation*.

Name	Value
waitSet	{"p1", "p2", "p3", "c3", "c4", "c5"}
▼ ▲ <Action line 46, col 9 to line 47, col 62 of module b...	State (num = 26)
buffer	<<"m1", "m1">>
waitSet	{"p1", "p2", "p3", "c4", "c5"}
▼ ▲ <Action line 46, col 9 to line 47, col 62 of module b...	State (num = 27)
buffer	<<"m1">>
waitSet	{"p1", "p2", "p3", "c5"}
▼ ▲ <Action line 46, col 9 to line 47, col 62 of module b...	State (num = 28)
buffer	<< >>
waitSet	{"p1", "p2", "p3"}
▼ ▲ <Action line 46, col 9 to line 47, col 62 of module b...	State (num = 29)
buffer	<< >>
waitSet	{"p1", "p2", "p3", "c1"}
▼ ▲ <Action line 46, col 9 to line 47, col 62 of module b...	State (num = 30)
buffer	<< >>
waitSet	{"p1", "p2", "p3", "c1", "c2"}
▼ ▲ <Action line 46, col 9 to line 47, col 62 of module b...	State (num = 31)
buffer	<< >>
waitSet	{"p1", "p2", "p3", "c1", "c2", "c3"}
▼ ▲ <Action line 46, col 9 to line 47, col 62 of module b...	State (num = 32)
buffer	<< >>
waitSet	{"p1", "p2", "p3", "c1", "c2", "c3", "c4"}
▼ ▲ <Action line 46, col 9 to line 47, col 62 of module b...	State (num = 33)
buffer	<< >>
waitSet	{"p1", "p2", "p3", "c1", "c2", "c3", "c4", "c5"}

# THE BUG

- Condition variable shared between producers and consumer
- On producer signal other producer make wake up instead of consumer
- Bug is very hard to reproduce since 30 specific steps need to happen
- *NotifyAll* strategy fixes issue with deadlock.
- If number of threads  $> 2 * \text{buffer capacity}$  algorithm is not deadlock free.

# NOTIFY\_ALL() VS NOTIFY()



If ..., you **share a condition variable** between multiple predicates, you **must always broadcast**, never signal;  
*Book: Programming with POSIX Threads by David R. Butenhof*

# AIORWLOCK SPEC

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# AIORWLOCK – READ WRITE LOCK FOR ASYNCIO

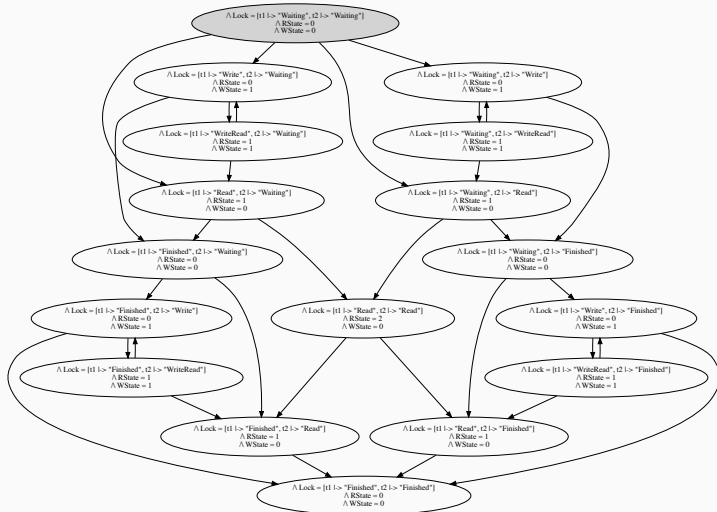
An RW lock allows concurrent access for read-only operations, while write operations require exclusive access, simple example:

```
1  import asyncio
2  import aiowlock
3
4  async def go():
5      rwlock = aiowlock.RWLock()
6
7      async with rwlock.writer:
8          print("inside writer: only one writer is possible")
9
10     async with rwlock.reader:
11         print("inside reader: multiple reader possible")
12
13 loop = asyncio.get_event_loop()
14 loop.run_until_complete(go())
```

# AIORWLOCK TRACE

Name	Value
▼ ▲ <Initial predicate>	State (num = 1)
▶ Lock	[t1  -> "Waiting", t2  -> "Waiting", t3  -> "Waiting"]
State	0
▼ ▲ <Action line 30, col 15 to line 33, col 40 of mod...	State (num = 2)
▼ Lock	[t1  -> "Write", t2  -> "Waiting", t3  -> "Waiting"]
● t1	"Write"
● t2	"Waiting"
● t3	"Waiting"
State	-1
▼ ▲ <Action line 26, col 18 to line 28, col 38 of mod...	State (num = 3)
▼ Lock	[t1  -> "WriteRead", t2  -> "Waiting", t3  -> "Waiting"]
● t1	"WriteRead"
● t2	"Waiting"
● t3	"Waiting"
State	0
▼ ▲ <Action line 22, col 18 to line 25, col 43 of mod...	State (num = 4)
▼ Lock	[t1  -> "WriteRead", t2  -> "Read", t3  -> "Waiting"]
● t1	"WriteRead"
● t2	"Read"
● t3	"Waiting"
State	1

# AIORWLOCK POSSIBLE STATES FOR 2 TASKS





# AIORWLOCK SPEC RESULTS

- In fact bug reveled itself on specification phase, before running any models.
- Only three steps required to reproduce issue.
- First aio-lib's project with formal verification!

# CONCLUSIONS

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# LIMITATIONS OF MODEL-CHECKING

- **State space explosion** number of states reachable by a system can quickly become huge, or even infinite
- **Not a replacement for tests** or other standard quality assurance methods
- **Formal methods are not a panacea**, but can increase confidence in a product's reliability if applied with care and skill

# Questions?



<http://github.com/jettify>

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