CrashTuner: Detecting Crash Recovery Bugs in Cloud Systems via Meta-info Analysis

SOSP2019

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Crash Recovery

- Recovery must be a first-class operation of distributed systems[1].

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Crash Recovery

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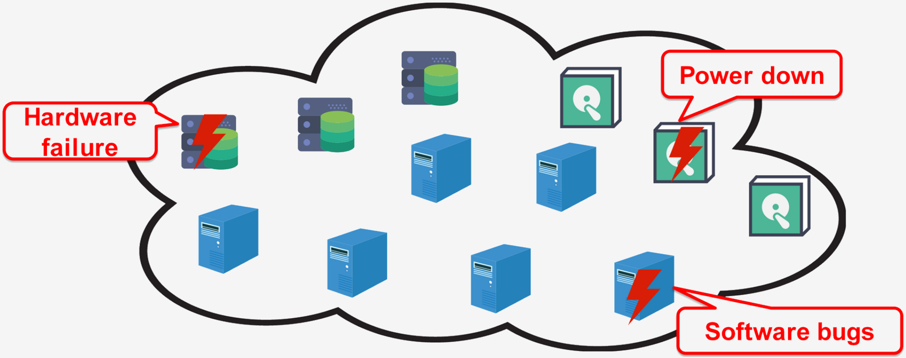
  - Nodes can crash due to different reasons.[2]



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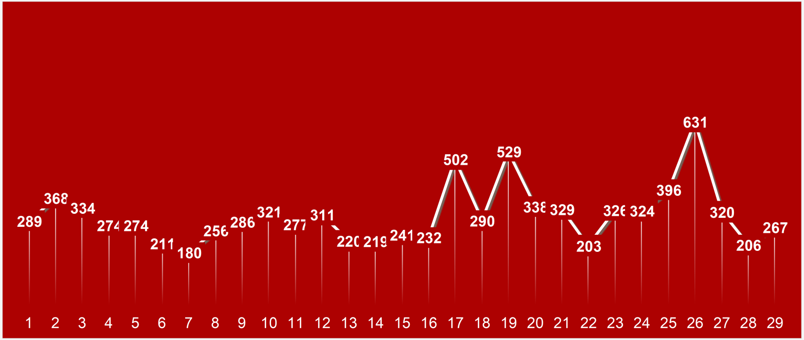
  - Node Crash Events can be common in a large cluster(At least 180).[4]



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[4] Mohammad Reza Mesbahi, Amir Masoud Rahmani, and Mehdi Hosseinzadeh (2017). "Cloud dependability analysis: Characterizing google cluster infrastructure reliability". In: *2017 3th International Conference on Web Research (ICWR)*. IEEE, pp. 56–61.

Crash-Recovery Bugs and Detection

- Crash Recovery Code can be buggy and often result in catastrophic failure.[5]

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  - Model checking: Inefficient and requires manual specifications[7].
- Crash-Recovery bugs still widely exist in distributed system.[8]
  - Distributed systems have large state space to explore.
  - Crash-Recovery bugs can only be triggered when nodes crash under special timing conditions.

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This paper: CrashTuner

- A new approach to automatically detect crash-recovery bugs in distributed systems .
  - 21 new crash-recovery bugs (including 10 critical bugs).
  - Test 5 distributed systems in 35 hours.

Bug ID	Priority	Scenario	Status	Symptom	Meta-info
YARN-9238	Critical	pre-read	Fixed	Allocating containers to removed ApplicationAttempt	ApplicationAttemptId
YARN-9165	Critical	pre-read	Fixed	Scheduling the removed container	ContainerId
YARN-9193	Critical	pre-read	Fixed	Allocating container to removed node	NodeId
YARN-9164(2)	Critical	pre-read	Fixed	Cluster down due to using the removed node	NodeId
YARN-9201	Major	pre-read	Fixed	Invalid event for current state of ApplicationAttempt	ContainerId
HDFS-14216(2)	Critical	pre-read	Fixed	Request fails due to removed node	DataNodeInfo
YARN-9194	Critical	pre-read	Fixed	Invalid event for current state of ApplicationAttempt	ApplicationId
HBASE-22041	Critical	post-write	Unresolved	Master startup node hang	ServerName
HBASE-22017	Critical	pre-read	Fixed	Master fails to become active due to removed node	ServerName
YARN-8650(2)	Major	pre-read	Fixed	Invalid event for current state of Container	ContainerId
YARN-9248	Major	pre-read	Fixed	Invalid event for current state of Container	ApplicationAttemptId
YARN-8649	Major	pre-read	Fixed	Resource Leak due to removed container	ApplicationId
HBASE-21740	Major	post-write	Fixed	Shutdown during initialization causing abort	MetricsRegionServer
HBASE-22050	Major	pre-read	Unresolved	Atomic violation causing shutdown aborts	RegionInfo
HDFS-14372	Major	pre-read	fixed	Shutdown before register causing abort	BPOfferService
MR-7178	Major	post-write	Unresolved	Shutdown during initialization causing abort	TaskAttemptId
HBASE-22023	Trivial	post-write	Unresolved	Shutdown during initialization causing abort	MetricsRegionServer
CA-15131	Normal	pre-read	Unresolved	Request fails due to using removed node	InetAddressAndPort

The paper: CrashTuner

How does CrashTuner do it?

Findings

- Existing Crash-Recovery bugs can be easily triggered when nodes:

Figure: 116 Crash-Recovery Bugs from four distributed Systems.

hadoop HDFS	hadoop YARN	APACHE HBASE	Apache Zookeeper
Distributed File System	Distributed Resource Manager System	Distributed Database	Centralized service
Master/slave	Master/slave	Master/slave	Master/slave based on leader election

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Findings

- Existing Crash-Recovery bugs can be easily triggered when nodes:
  - Crash before reading variables
  - Crash after writing variables .
- One thing in common : All these variables are **meta-info** variables.

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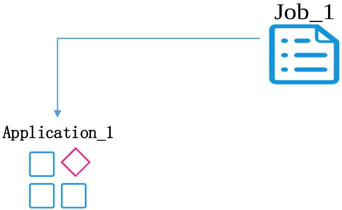
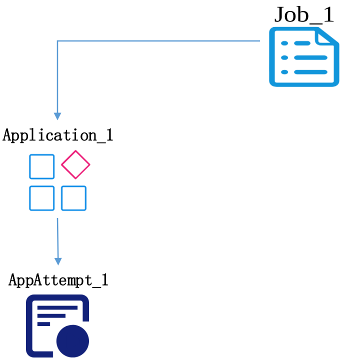
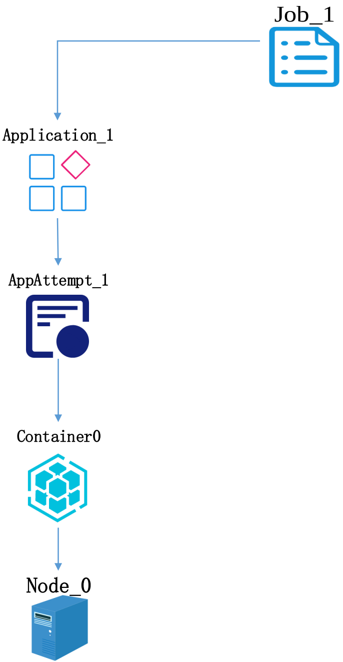
What are meta-info variables?

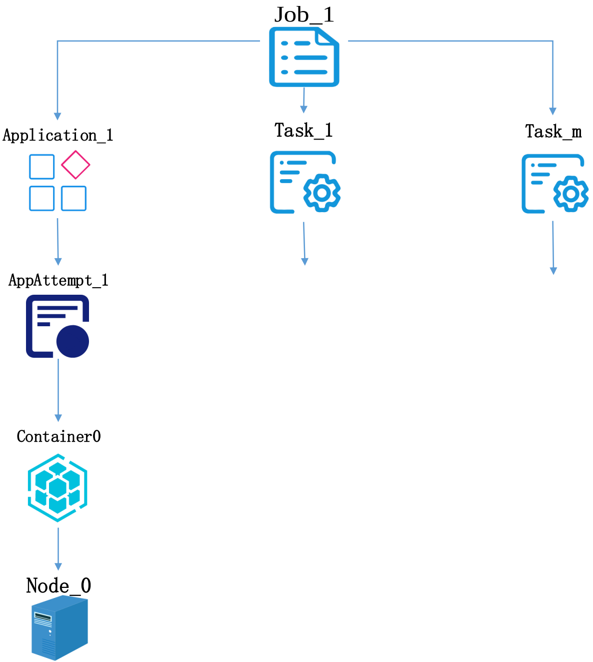
A simplified YARN example

Job_1

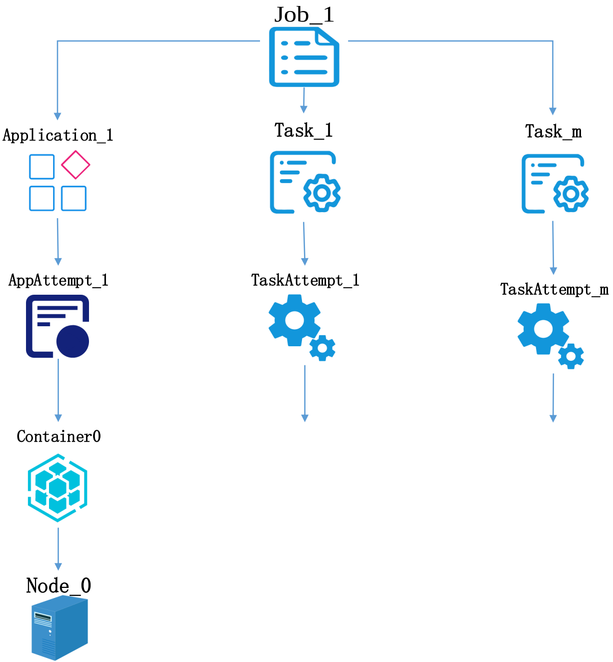

Job_1
Application_1

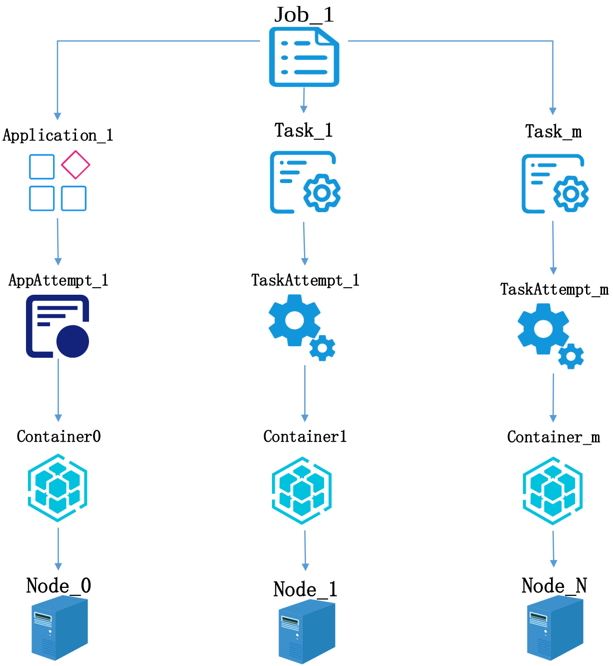

Job_1
Application_1
AppAttempt_1

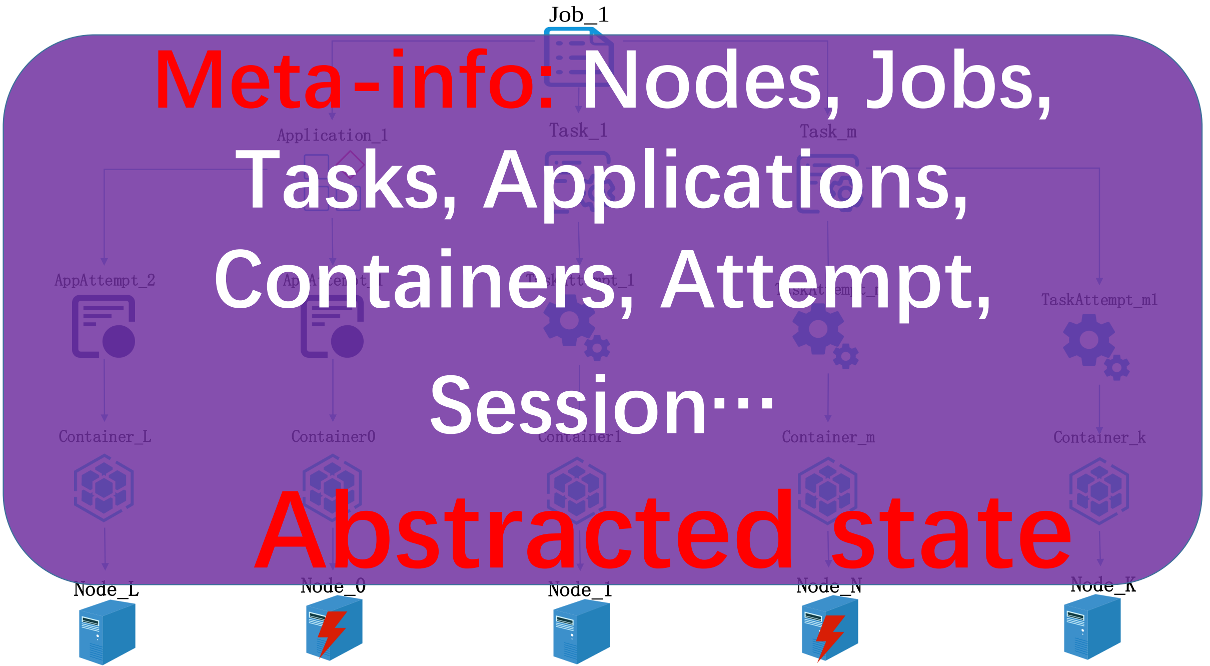

Job_1
Application_1
AppAttempt_1
Container0
Node_0

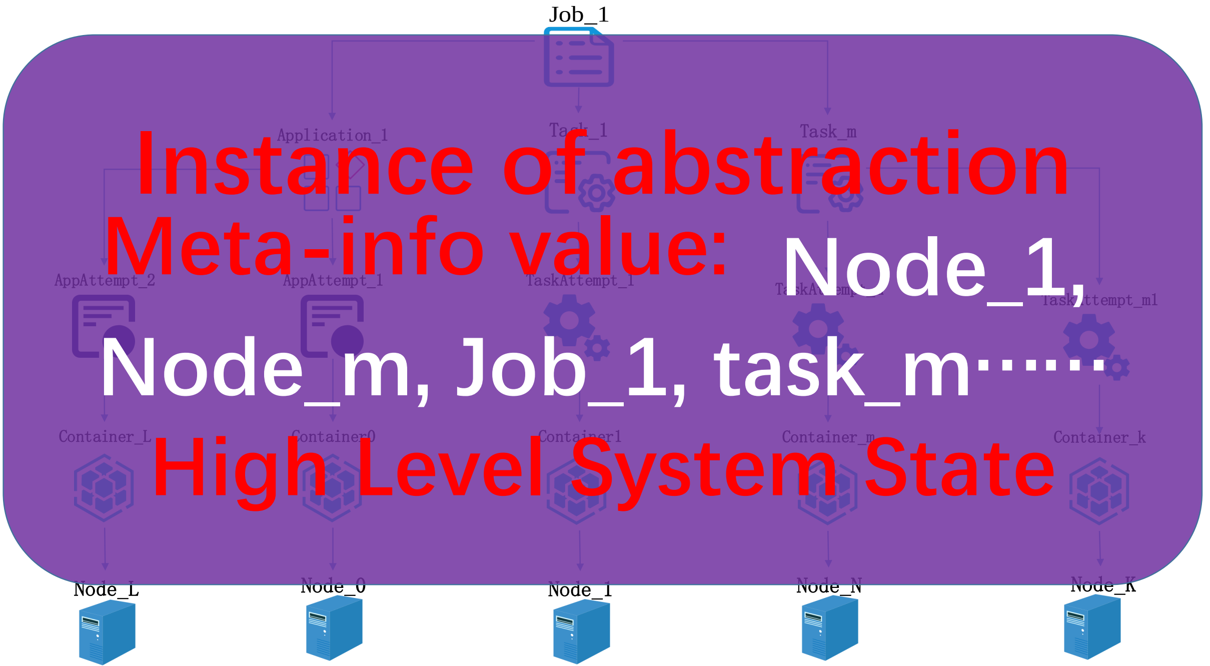


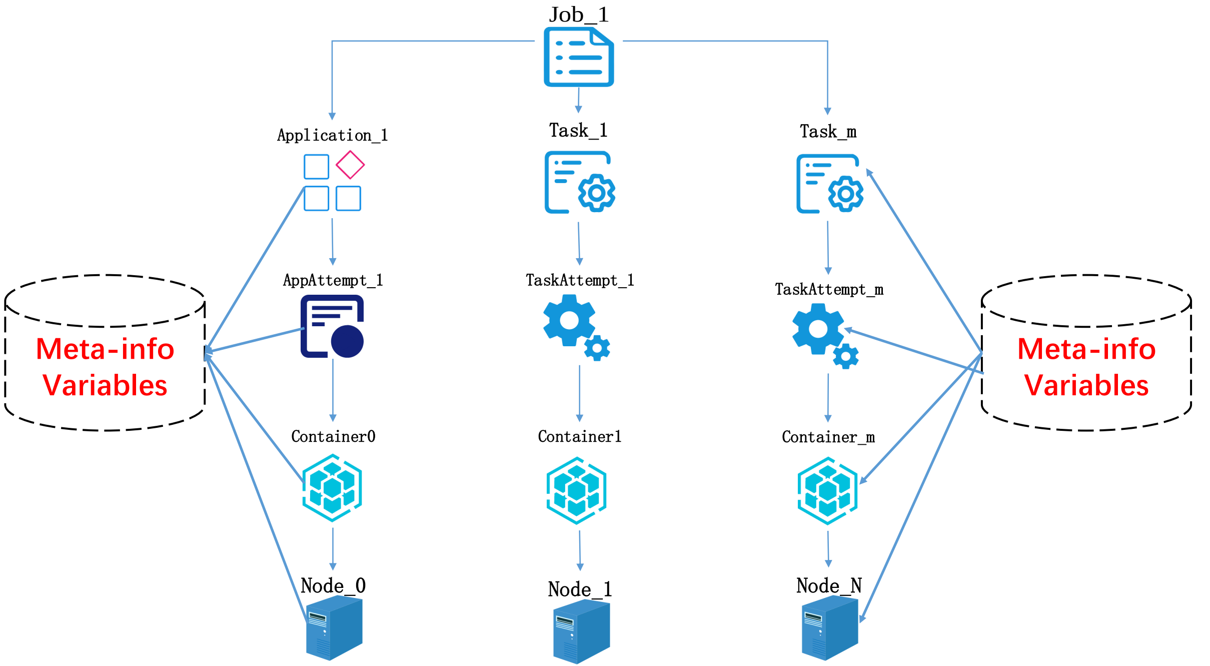
Job_1
Application_1
Task_1
Task_m
AppAttempt_1
Container0
Node_0


Job_1
Application_1
Task_1
Task_m
AppAttempt_1
TaskAttempt_1
TaskAttempt_m
Container0
Node_0


Job_1
Application_1
Task_1
Task_m
AppAttempt_1
TaskAttempt_1
TaskAttempt_m
Container0
Container1
Container_m
Node_0
Node_1
Node_N


Meta-info: Nodes, Jobs, Tasks, Applications, Containers, Attempt, Session…
Abstracted state
Job_1
Application_1
Task_1
Task_m
AppAttempt_2
TaskAttempt_m1
Container_L
Container0
Container1
Container_m
Container_k
Node_L
Node_0
Node_1
Node_N
Node_K

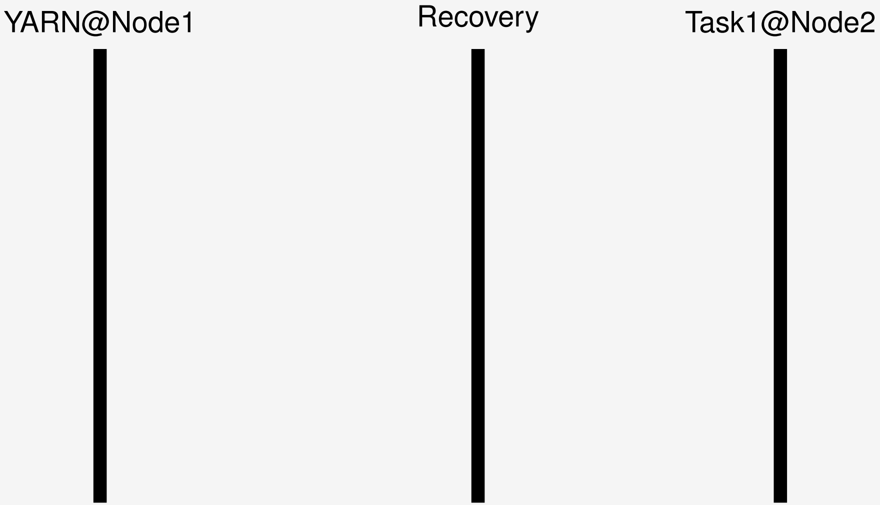

Job_1
Application_1
Task_1
Task_m
Instance of abstraction
Meta-info value: Node_1,
Node_m, Job_1, task_m……
AppAttempt_2
AppAttempt_1
TaskAttempt_1
TaskAttempt_m1
Container_L
Container0
Container1
Container_m
Container_k
High Level System State
Node_L
Node_0
Node_1
Node_N
Node_K


Job_1
Application_1
Task_1
Task_m
AppAttempt_1
TaskAttempt_1
TaskAttempt_m
Meta-info
Variables
Meta-info
Variables
Container0
Container1
Container_m
Node_0
Node_1
Node_N

Bug Example

Node Crashes before Reading meta-info variables

New Bug (YARN-9238) detected by CrashTuner



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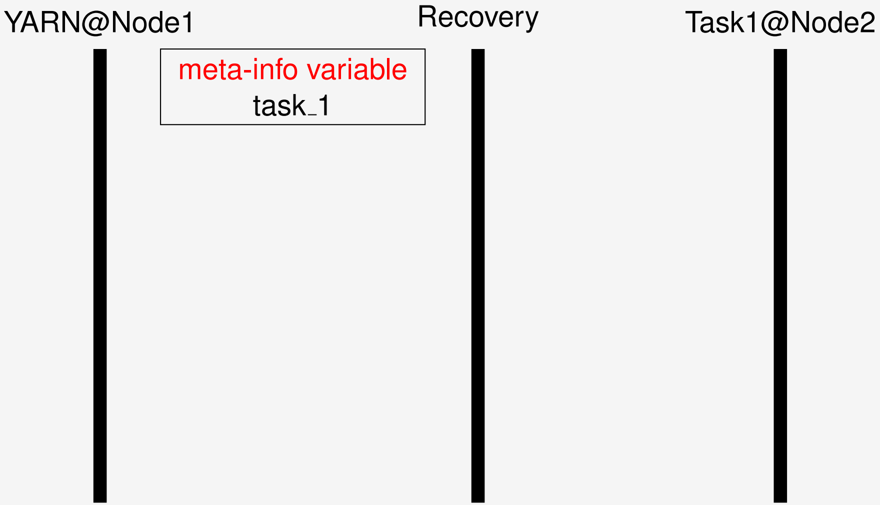

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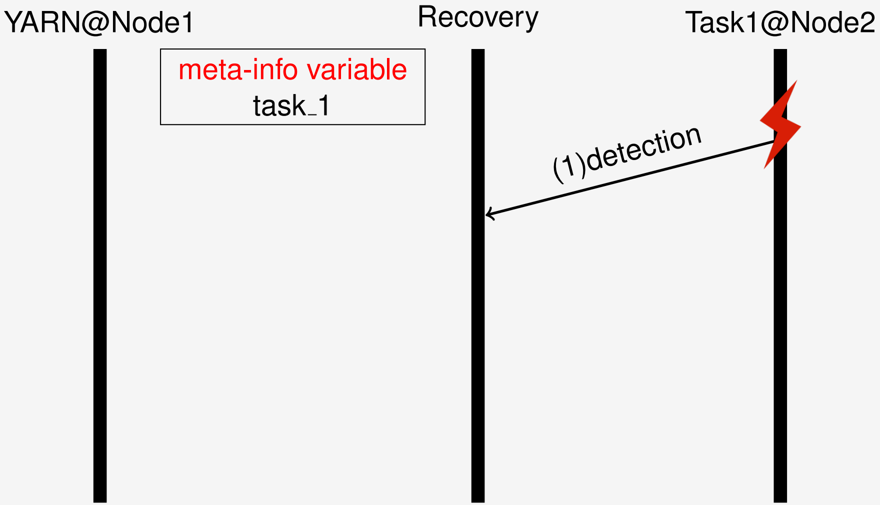

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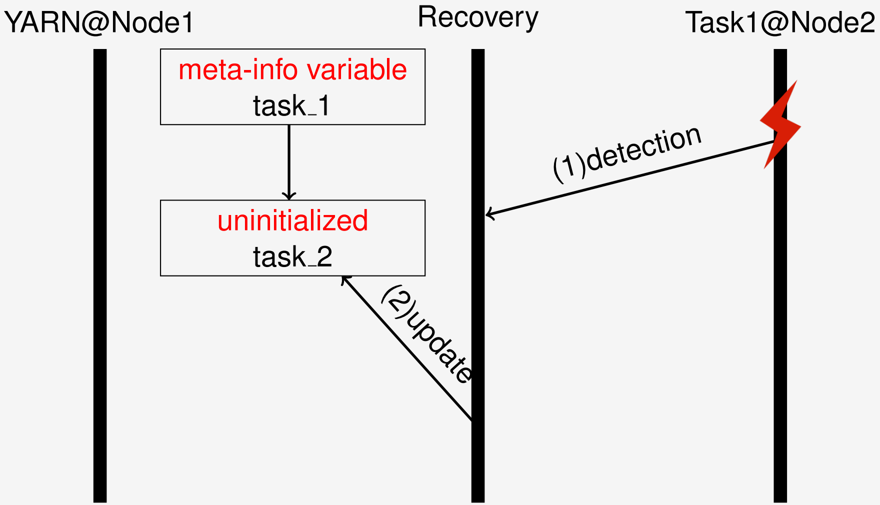

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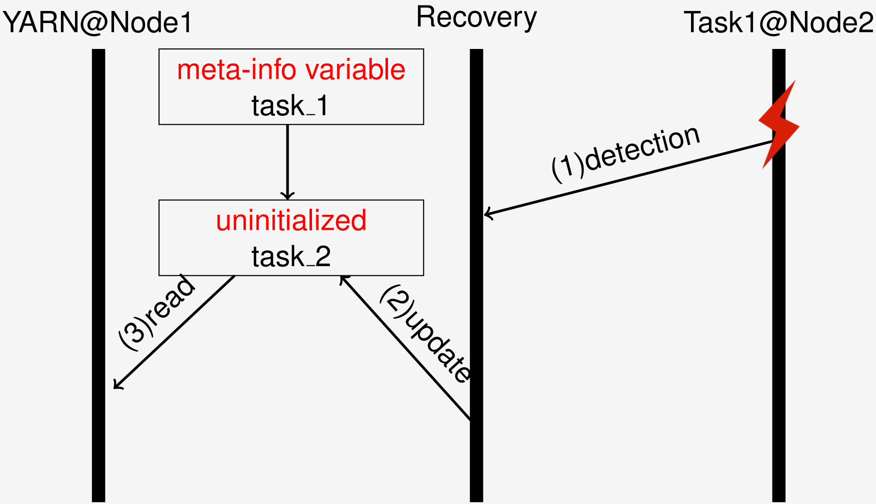

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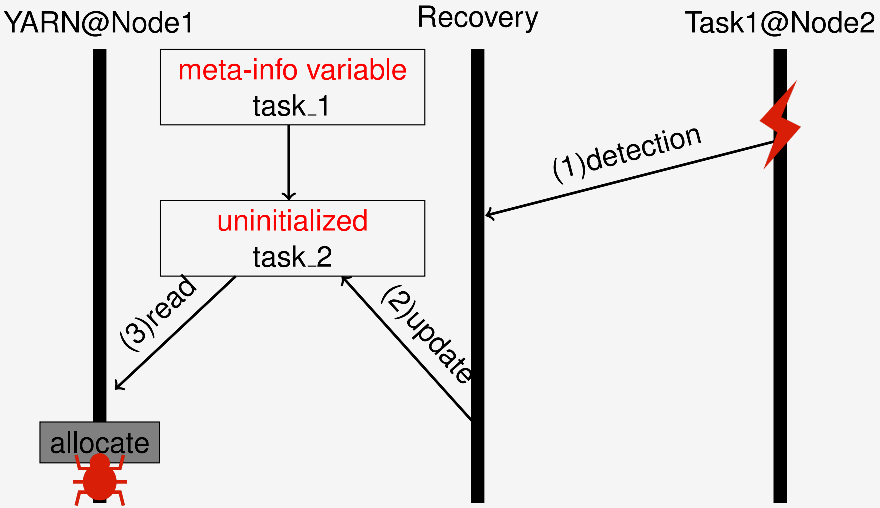
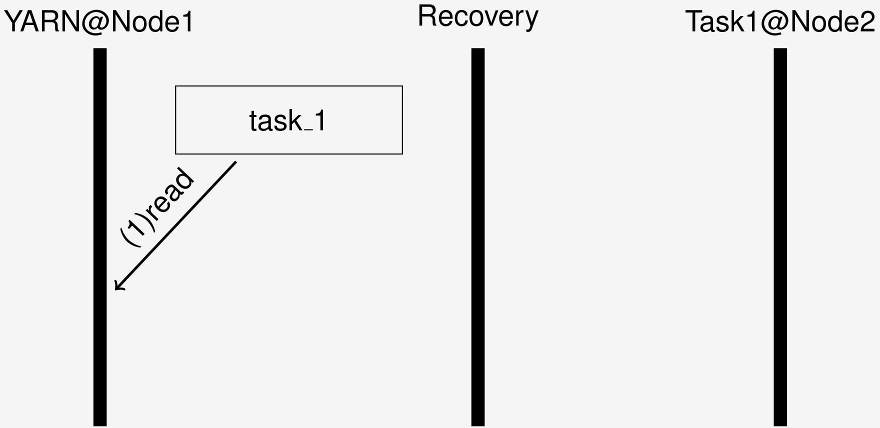


How CrashTuner Detected it?

Inject sleep and crash before reading the variable



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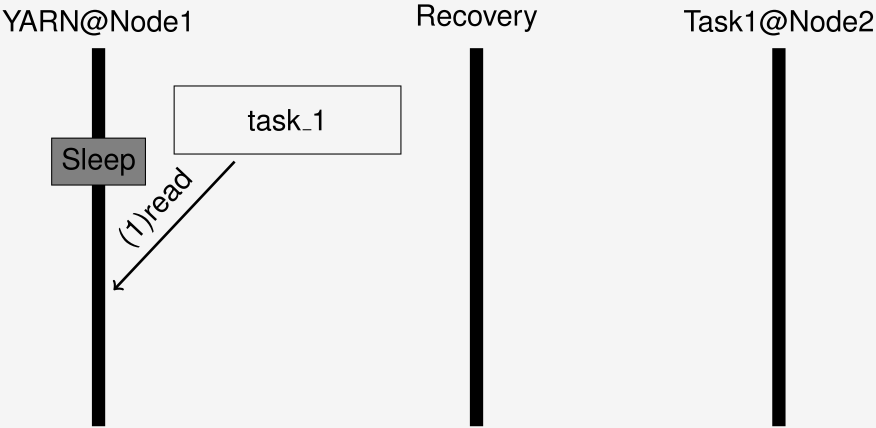

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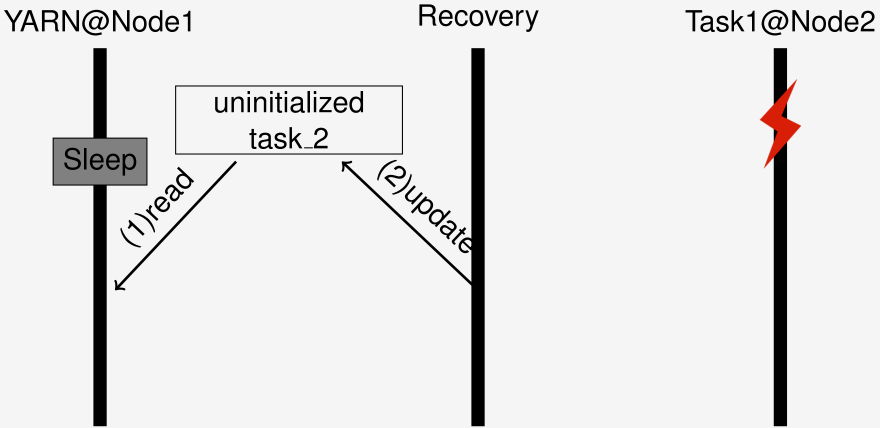

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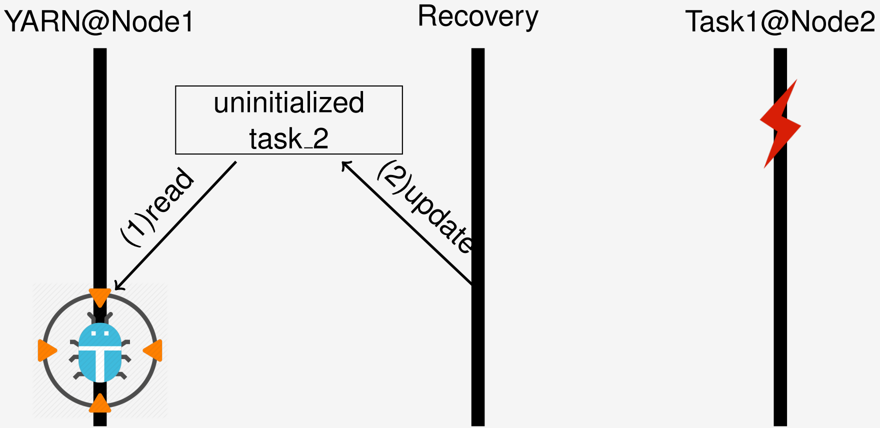
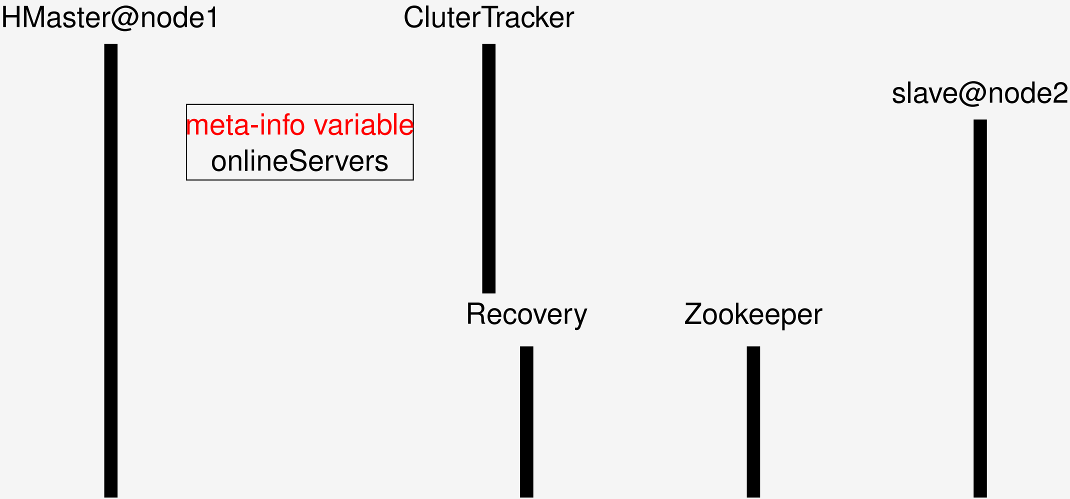


Bug Example

Node Crashes after writing meta-info variables

New Bug (HBASE-22041) detected by CrashTuner



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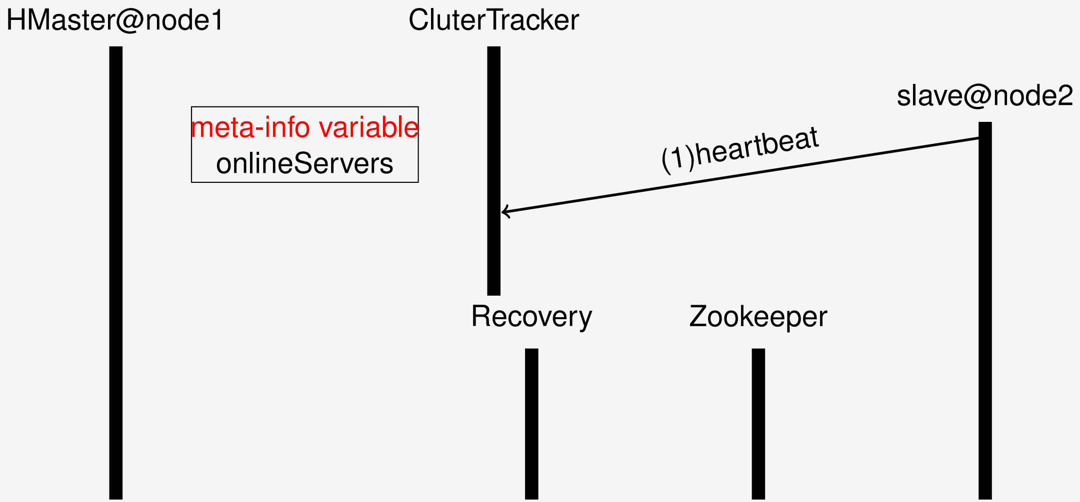

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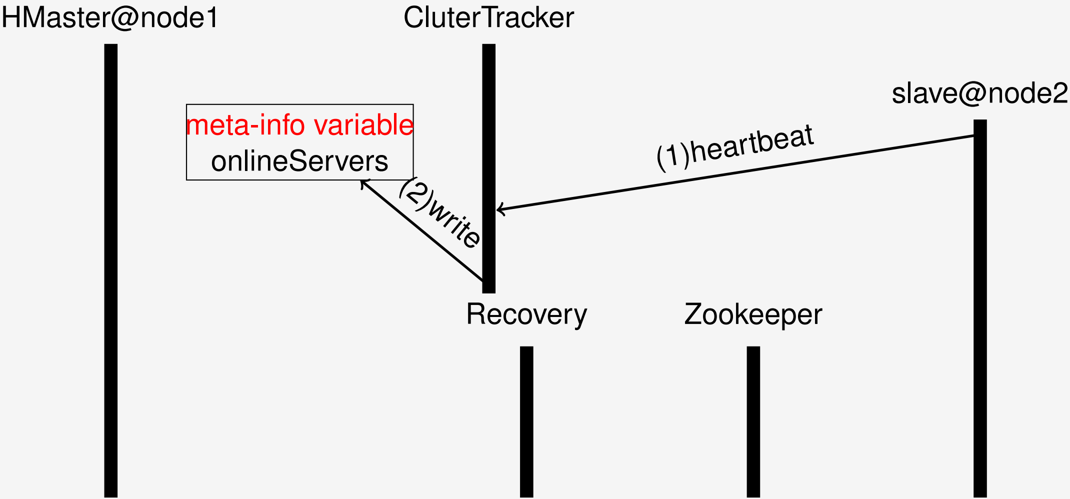

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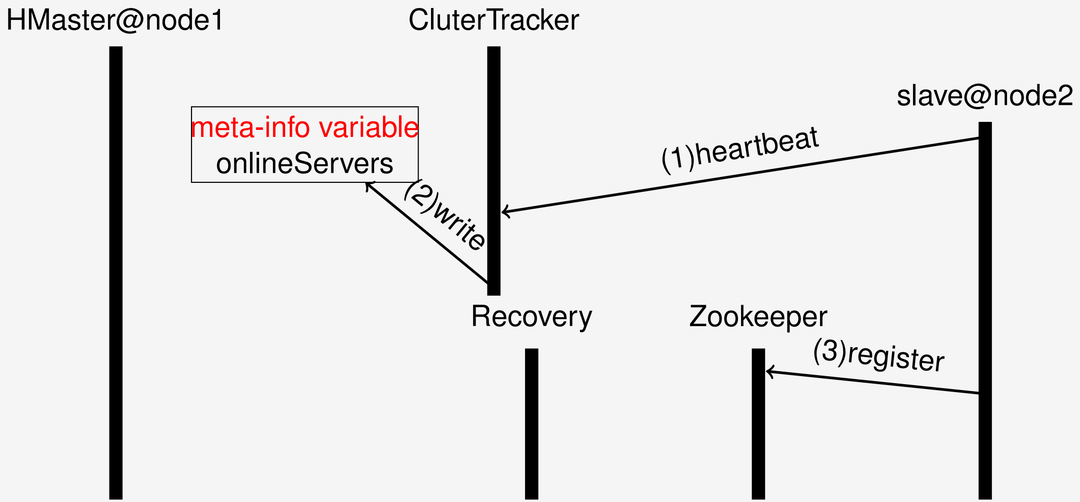

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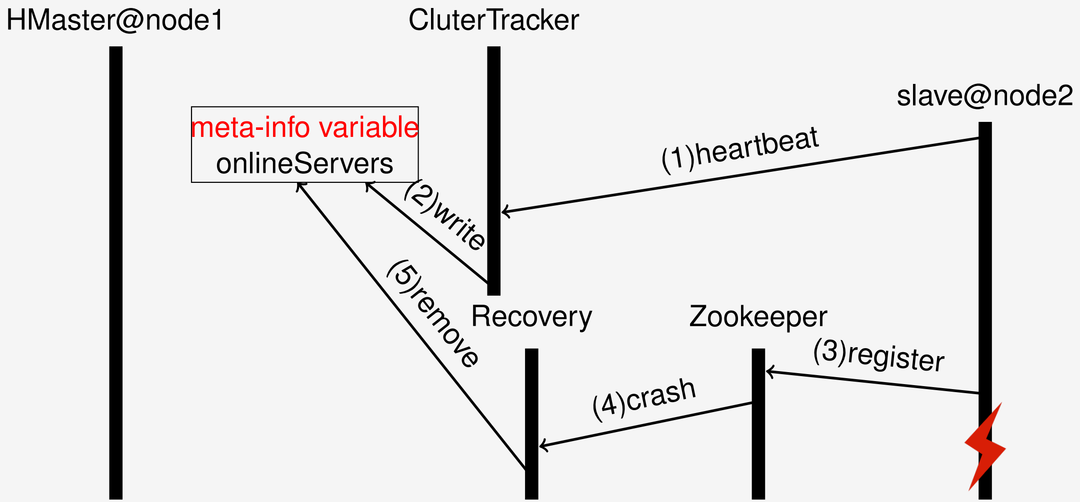

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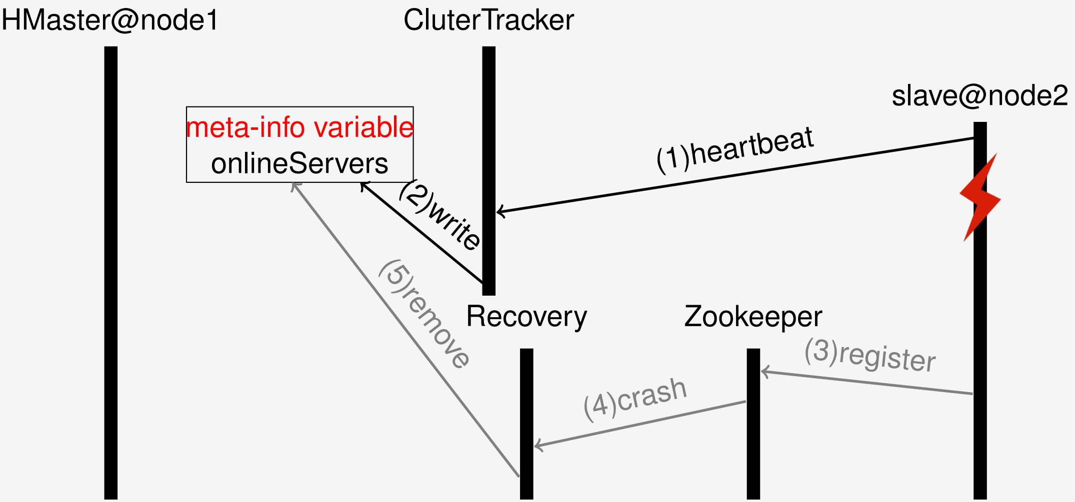

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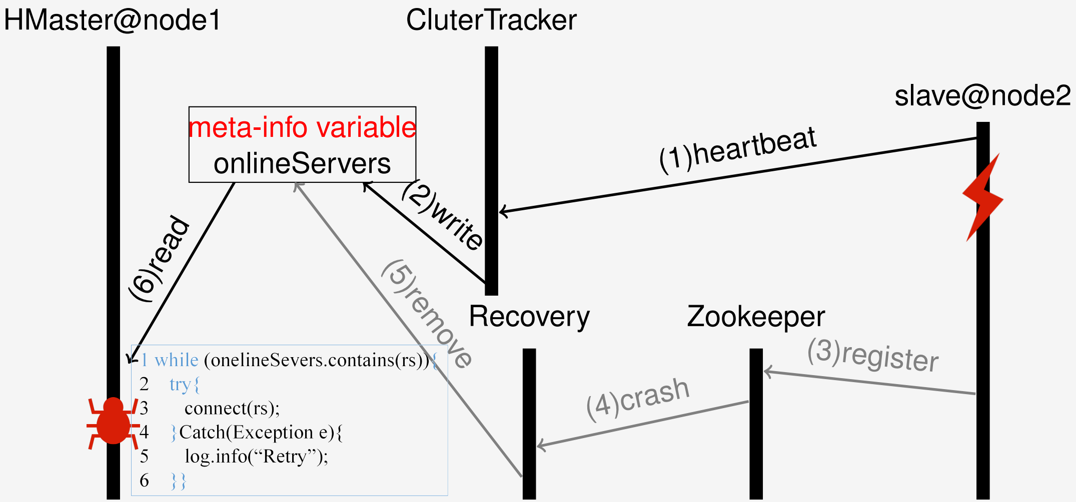
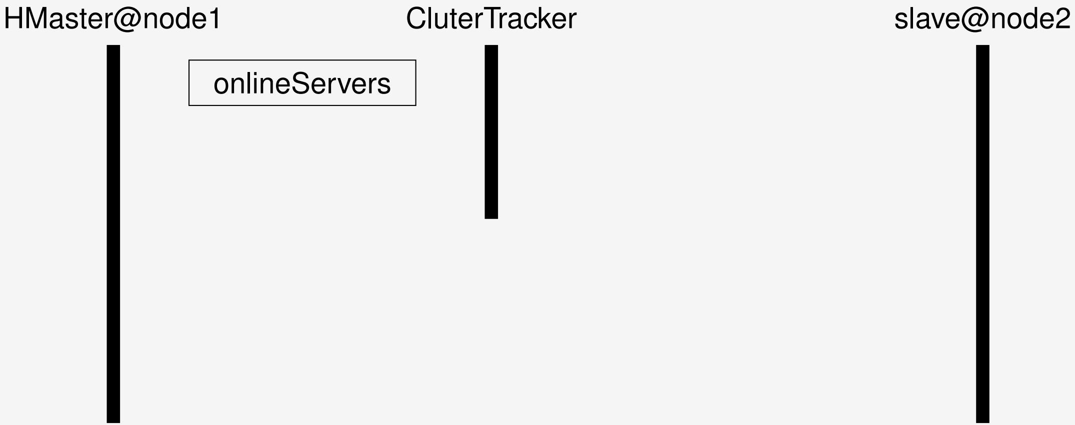


How CrashTuner detected it

Inject crash after writing the variable



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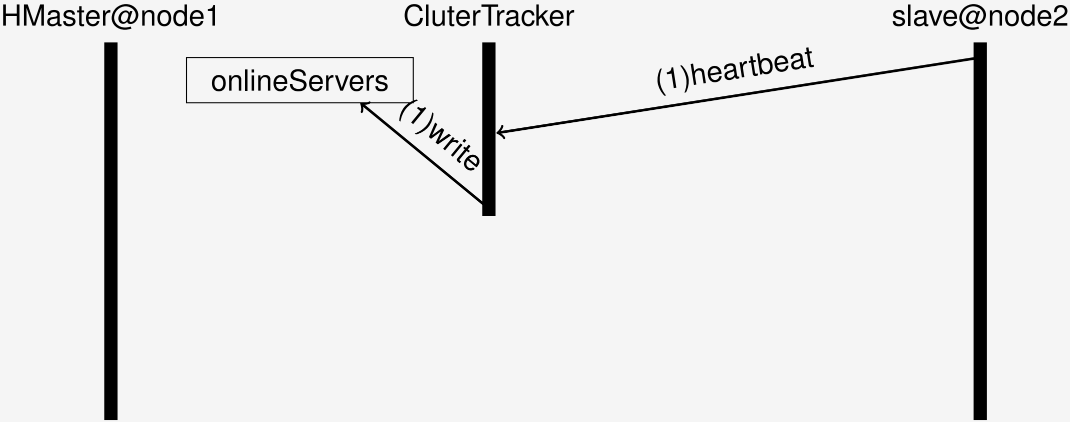

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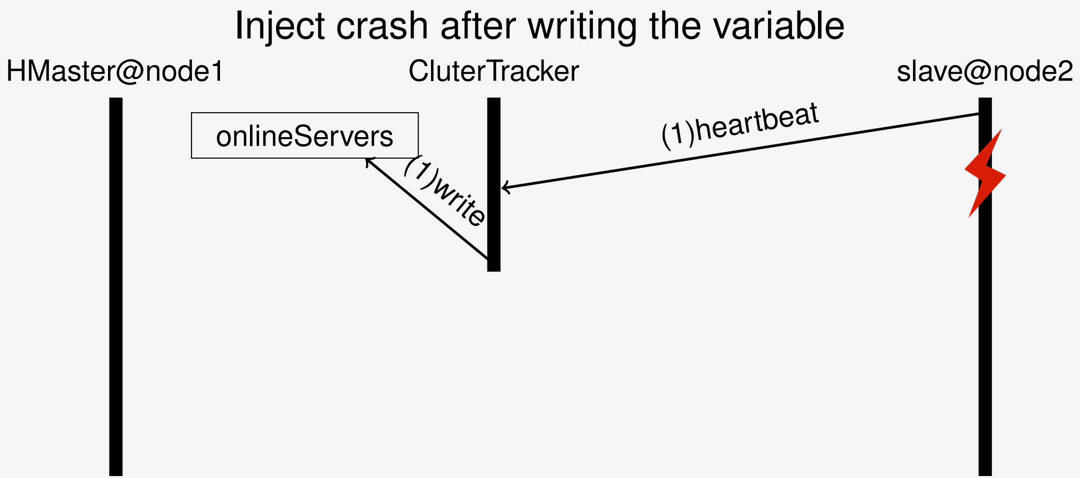

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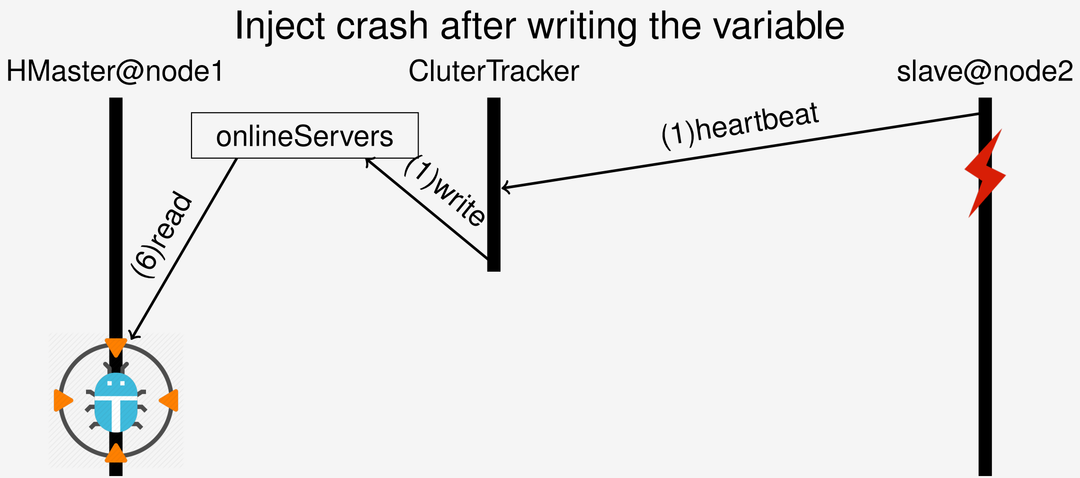

Meta-info variable identification

How to find meta-info variables?

Meta-info variable Identification

Node referencing variables are meta-info variables.

LOG.info("NodeManager from node " + address + " is assigned " + nodeId)

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Node referencing variables are meta-info variables.

LOG.info(”NodeManager from node ” + address + ” is assigned ” + nodeId)

NodeManager from node (.*) is assigned (.*)

Meta-info variable Identification

Node referencing variables are meta-info variables.

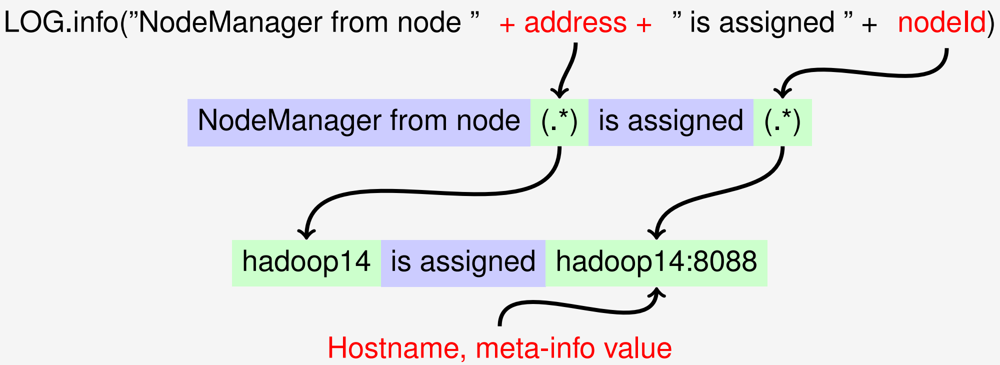
LOG.info(”NodeManager from node ” + address + ” is assigned ” + nodeId)

NodeManager from node (.*) is assigned (.*)

hadoop14 is assigned hadoop14:8088

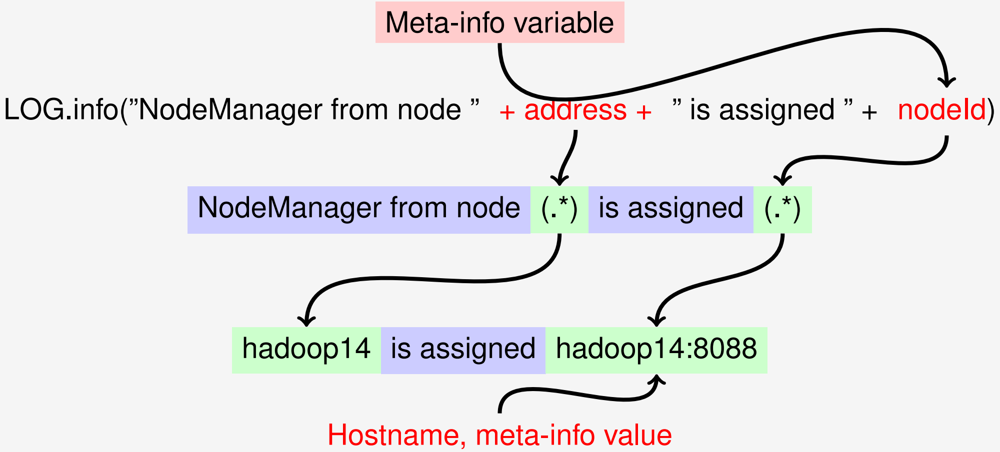
Meta-info variable Identification

Node referencing variables are meta-info variables.



Meta-info variable Identification

Node referencing variables are meta-info variables.



Meta-info variable Identification

Variables related to meta-info variable are meta-info variables.
Appearing in a same log instance.

Meta-info variable

LOG.info("Assigned Container" + containerId + " on host " + nodeId)

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Meta-info variable

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Meta-info variable

LOG.info(”Assigned Container” + containerId + ” to ” + attempt)

Meta-info variable Identification

Variables related to meta-info variable are meta-info variables.

Appearing in a same log instance.

Meta-info variable

```
LOG.info("Assigned Container" + containerId + " on host " + nodeId)
```

Meta-info variable

```
LOG.info("Assigned Container" + containerId + " to " + attempt)
```

Meta-info variable

Meta-info variable Identification

- Type based static analysis to discover meta-info variables not logged.

```
/* - tracks the state of all cluster nodes*/
public class ClusterNodeTracker<N extends SchedulerNode> {
private HashMap<NodeId, N> nodes = new HashMap<>();
}
```

Meta-info type

Meta-info variable

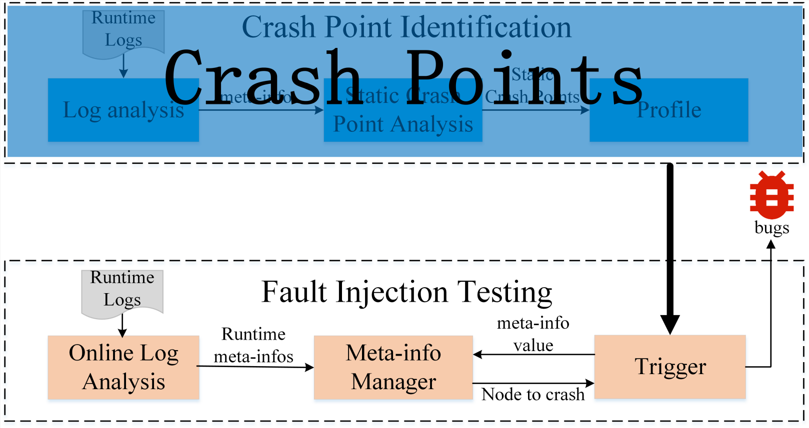
Crash Point

- Pre-read points of meta-info variables.

Crash Point

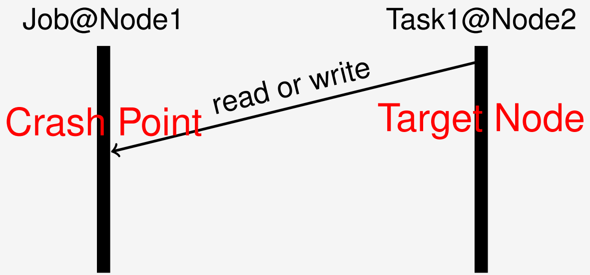
- Pre-read points of meta-info variables.
- Post-write points of meta-info variables.

Node to Crash



Node to Crash

Which node to Crash ?



Crash node2 at the crash point in node1.

Inferring the Target Node

Run time logs

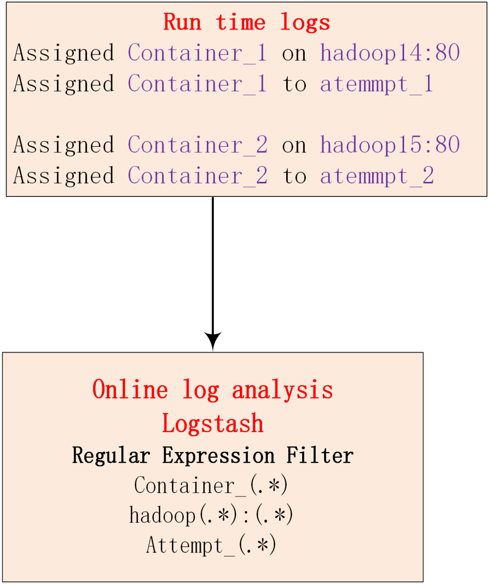
```
Assigned Container_1 on hadoop14:80
Assigned Container_1 to atemmpt_1

Assigned Container_2 on hadoop15:80
Assigned Container_2 to atemmpt_2
```

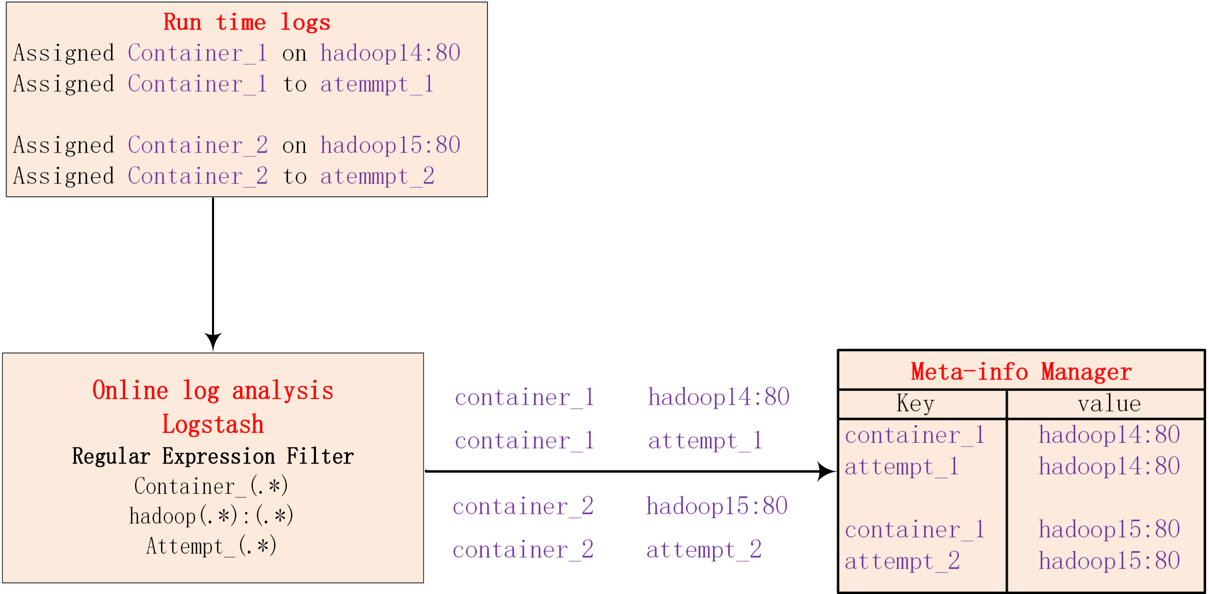
Container_1 and attempt_1 on hadoop14

Container_2 and attempt_2 on hadoop15

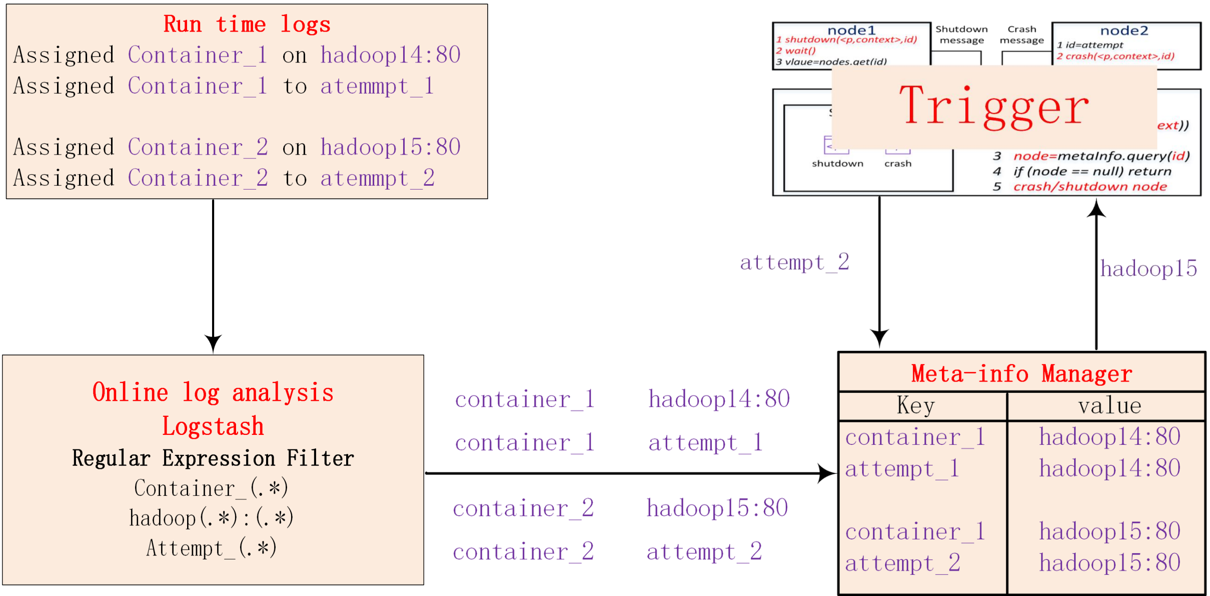
Inferring the Target Node



Inferring the Target Node



Inferring the Target Node



Evaluations

Table: Five distributed Systems under testing(Cassandra is not our bug-studied system).

System	Configure Change	Workload
Hadoop2/Yarn	enable opportunistic	Wordcount
HDFS	—	TestDFSIO,curl
HBase	—	PE,curl
Zookeeper	—	Smoketest
Cassandra	—	Stress

Evaluations

Table: The number of meta-info and crash point and test time.

System	# Meta-info			# Crash Points		Test time(h)
	Types	Fields	Access Points	Static	Dynamic	
Hadoop2/Yarn	107	1,251	5,109	1,524	453	17.39
HBase	34	733	4,032	920	257	8.27
HDFS	43	315	1,924	495	237	8.65
ZooKeeper	3	13	90	41	40	0.27
Cassandra	1	122	666	197	69	1.10
total	188	2,434	11,821	3,177	1,056	35.68

Evaluations

Table: The number of meta-info and crash point and test time.

System	# Meta-info			# Crash Points		Test time(h)
	Types	Fields	Access Points	Static	Dynamic	
Hadoop2/Ya[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]39
HBase	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]27
HDFS	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]5
ZooKeepe[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]27
Cassandr[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]10
total	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible].68

CrashTuner reduces 99.91% unnecessary crash points

CrashTuner reports 21 new bugs, 16 of them are already fixed

Bug ID	Type	Status	Symptom	Meta-info
YARN-1	pre-read	Fixed	Invalid event for current state of ApplicationAttempt	ContainerId
YARN-2	pre-read	Fixed	Invalid event for current state of ApplicationAttempt	ApplicationId
YARN-3	pre-read	Fixed	Scheduling the removed container	ContainerId
YARN-4	pre-read	Fixed	Allocating container to removed node	NodeID
YARN-5(2)	pre-read	Fixed	Cluster down due to using the lost node	NodeID
YARN-7(2)	pre-read	Fixed	Invalid event for current state of Container	ContainerId
YARN-9	pre-read	Fixed	Invalid event for current state of Container	ApplicationAttemptId
YARN-10	pre-read	Fixed	Resource Leak while Localizing file	ApplicationId
YARN-11	pre-read	Fixed	Allocating containers to removed ApplicationAttempt	ApplicationAttemptId
HBASE-12	post-write	Fixed	Shutdown before initialization causing abort	ServerName
HBASE-13	pre-read	Unresolved	Atomic violation causing shutdown fails	RegionInfo
HBASE-14	post-write	Unresolved	Master startup hang and print thousands of logs	ServerName
HBASE-15	post-write	Unresolved	Shutdown before initialization causing abort	ServerName
HBASE-16	pre-read	Fixed	Master Fails to become active due to LeaseException	ServerName
HDFS-17	pre-read	Fixed	Shutdown before register causing abort	DatanodeID
HDFS-18(2)	pre-read	Fixed	Request fails due to removed node	DataNodeInfo
MR-20	post-write	Unresolved	Shutdown before initialization causing abort	TaskAttemptId
CA-21	pre-read	Unresolved	Request fails due to removed node	InetAddressAndPort

Comparing to other fault injection strategies

CrashTuner report one bug in 50.29 runs within 1.70 hours.

- Random fault injection: 3 bugs, 1 bug per 5000 runs within 90.83 hours
- IO around crash injection, 1 bugs, 1 bug per 4500 runs within 156.88 hours
- All bugs can be detected by CrashTuner.

Comparing to other fault injection strategies

CrashTuner report one bug in 50.29 runs within 1.70 hours.

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- IO around crash injection, 1 bugs, 1 bug per 4500 runs within 156.88 hours
- All bugs can be detected by CrashTuner.

CrashTuner is much more Efficient and Effective than random crash injection and IO around crash injection

Limitations and Future Work

- CrashTuner maybe not good enough to test system with Bad Log Quality.
  - Developer can annotate the meta-info type.
- CrashTuner only inject one crash.
  - We can extend CrashTuner to test two or more crash events.
- CrashTuner only test Java based system.
  - Our study on k8s (implemented with Golang) shows that it also have meta-info related crash-recovery bugs.
  - We are extending CrashTuner to work with System written by Golang and C++.

Relate Works

- Crash-recovery bug studies.
  - CBSDB[9],TaxDC[10], CREB[11]
- Crash-recovery bug detection
  - Fault injection:Fate[12],Fcatch[13]
  - Model checking:FlyMC[EuroSys2019],SAMC[OSDI2014]
- Log analysis for distribute systems
  - Stitch[OSDI2016], Iprof[OSDI2014]

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[10] Tanakorn Leesatapornwongsa et al. (2016). "TaxDC: A Taxonomy of Non-Deterministic Concurrency Bugs in Datacenter Distributed Systems". In: *Proceedings of the Twenty-First International Conference on Architectural Support for Programming Languages and Operating Systems*. ASPLOS '16. Atlanta, Georgia, USA: ACM, pp. 517–530. ISBN: 978-1-4503-4091-5. DOI: 10.1145/2872362.2872374. URL: http://doi.acm.org/10.1145/2872362.2872374.

[11] Yu Gao et al. (2018). "An Empirical Study on Crash Recovery Bugs in Large-Scale Distributed Systems". In: *Proceedings of the 26th ACM Joint European Software Engineering Conference and Symposium on the Foundations of Software Engineering*. ESEC/FSE 2018.

[12] Haryadi S Gunawi et al. (2011). "FATE and DESTINI: A framework for cloud recovery testing". In: *Proceedings of NSDI'11: 8th USENIX Symposium on Networked Systems Design and Implementation*, p. 239.

[13] Haopeng Liu et al. (2018). "Fcatch: Automatically detecting time-of-fault bugs in cloud systems". In: *ACM SIGPLAN Notices* 53.2, pp. 419–431.

Conclusion

Abstraction is so fundamental that sometimes we forget its importance![14]
—Remzi H. Arpaci-Dusseau and Andrea C. Arpaci-Dusseau

[14] Remzi H. Arpaci-Dusseau and Andrea C. Arpaci-Dusseau (2018). *Operating Systems: Three Easy Pieces*. 1.00. Arpaci-Dusseau Books.

Conclusion

Abstraction is so fundamental that sometimes we forget its importance![14]

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Meta-info is a well-suited abstraction for distributed systems!

[14] Remzi H. Arpaci-Dusseau and Andrea C. Arpaci-Dusseau (2018). *Operating Systems: Three Easy Pieces*. 1.00. Arpaci-Dusseau Books.

Thank you!

Any Questions?