

面向分布式系统的复制数据类型理论研究概述

(CCF 2018 第九届优博论坛)

魏恒峰

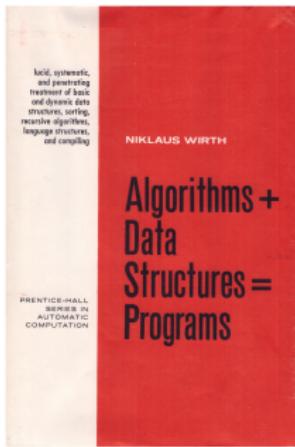
南京大学软件所

2018 年 08 月 08 日



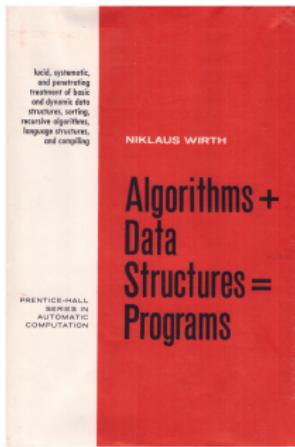
Abstract Data Types (ADT) [Liskov and Zilles, 1974]

(单线程; 顺序语义)



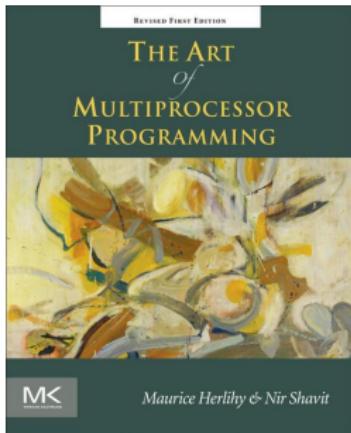
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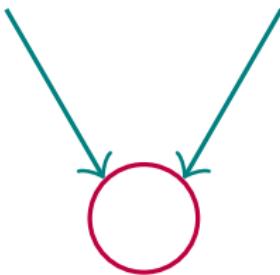
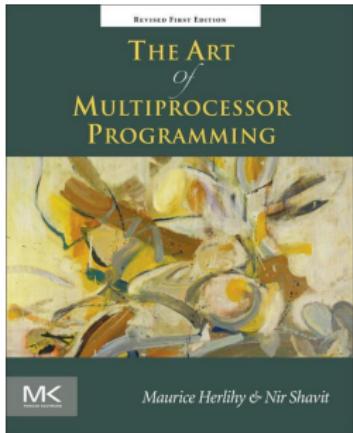
Concurrent Data Types [Herlihy and Wing, 1990]

(多线程; 并发语义)



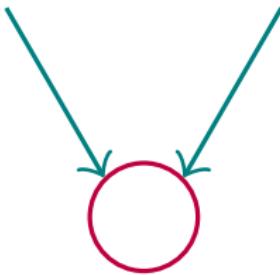
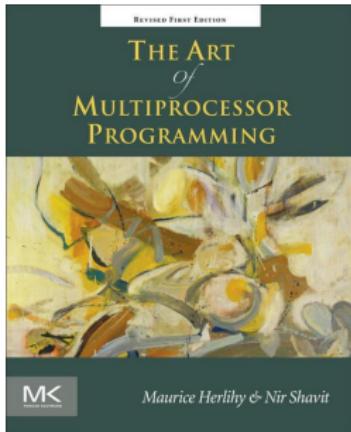
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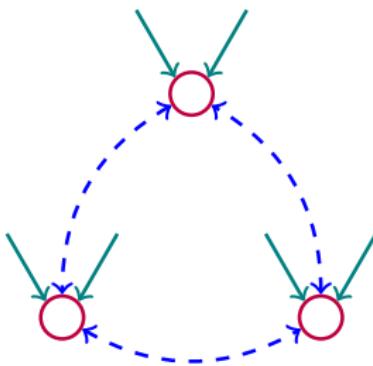
PL (Programming Language)

Replicated Data Types (RDT; \approx 2010 年) [Burckhardt et al., 2014]

(多副本; 复制语义)

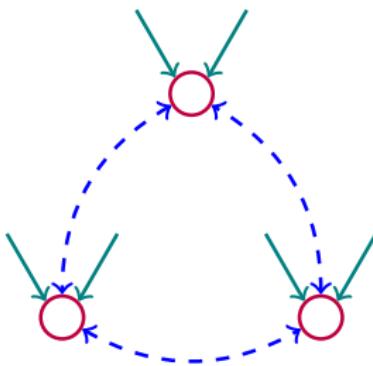
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DC (Distributed Computing)

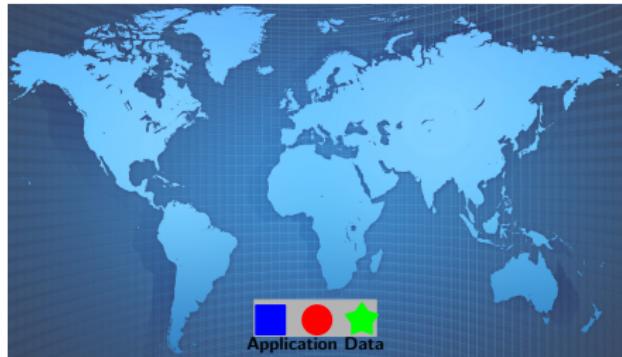
新平台：大规模分布式系统



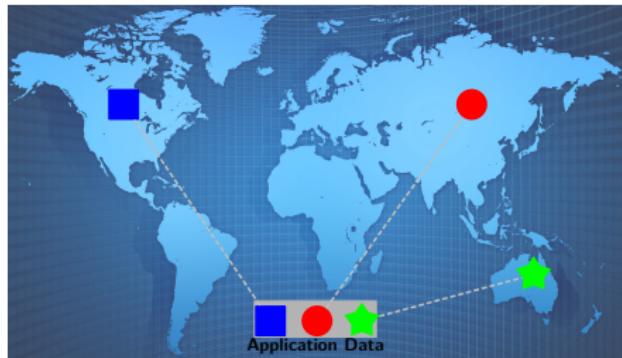
新平台：大规模分布式系统



低延迟 高可用性 (4 个 9) 高容错性 高可扩展性

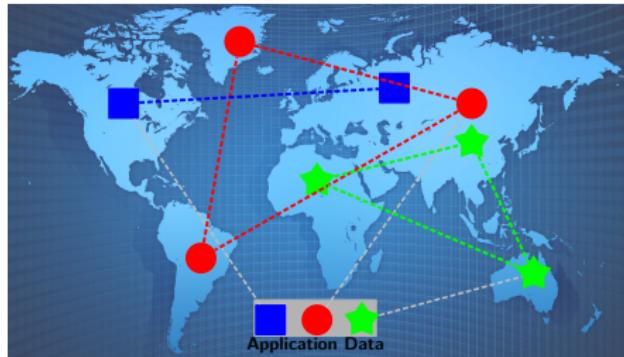


分布数据 (distributed data):



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1. 分区 (partition): 水平扩展



分布数据 (distributed data):

1. 分区 (partition): 水平扩展
2. 副本 (replication): 就近访问, 容灾备份

复制数据类型 [Shapiro et al., 2011a]

- ▶ Read/Write Register
- ▶ Counter
- ▶ Set
- ▶ List
- ▶ HashMap
- ▶ Disjoint Set
- ▶ Graph
- ▶ ...

What's
new?

新问题, 新挑战

What's
new?

新问题, 新挑战

Replicated Data Types: Specification, Verification, Optimality

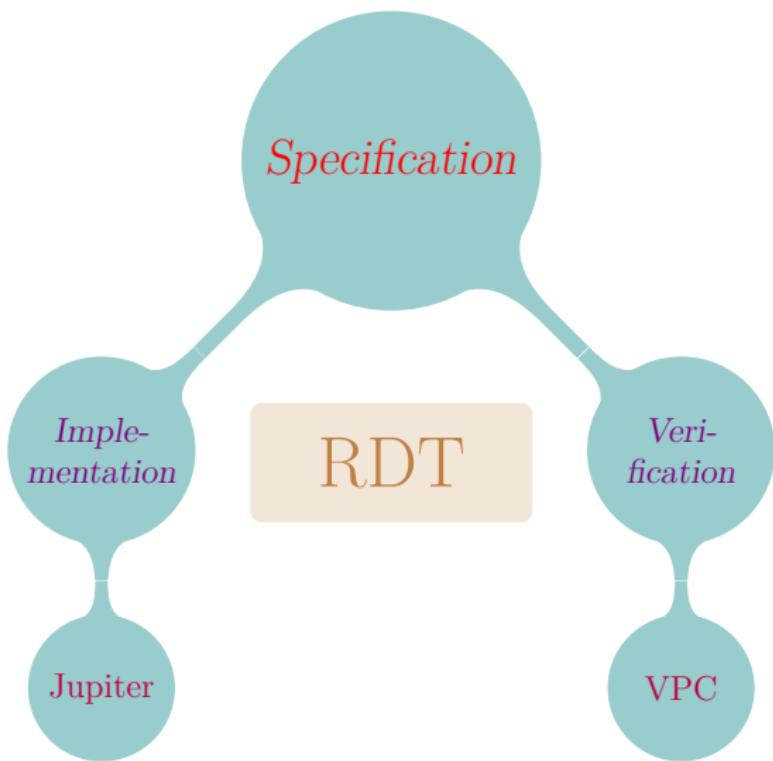
Sebastian Burckhardt

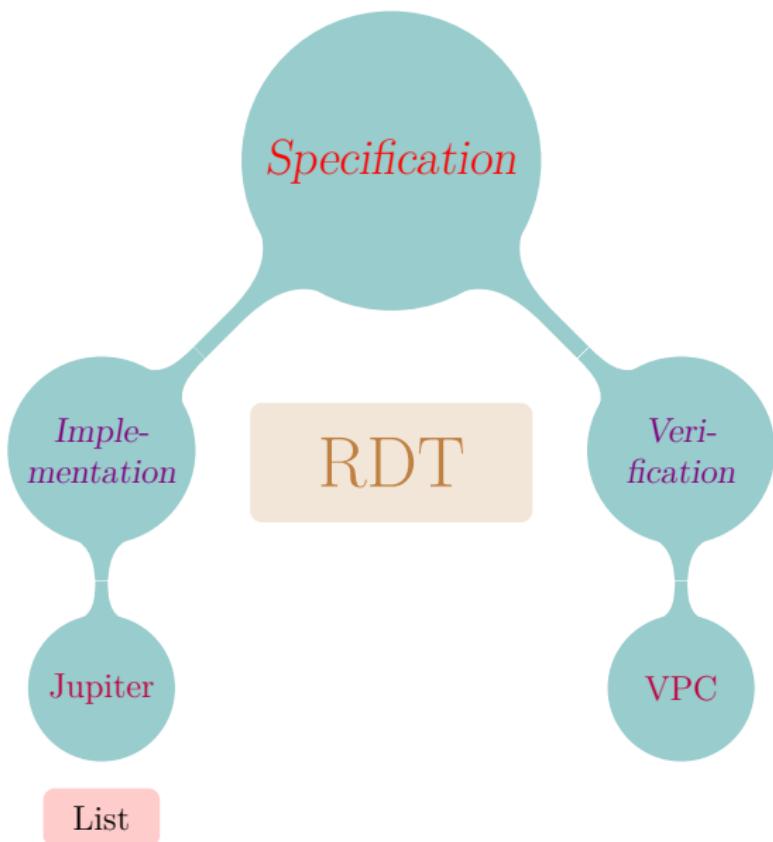
Alexey Gotsman

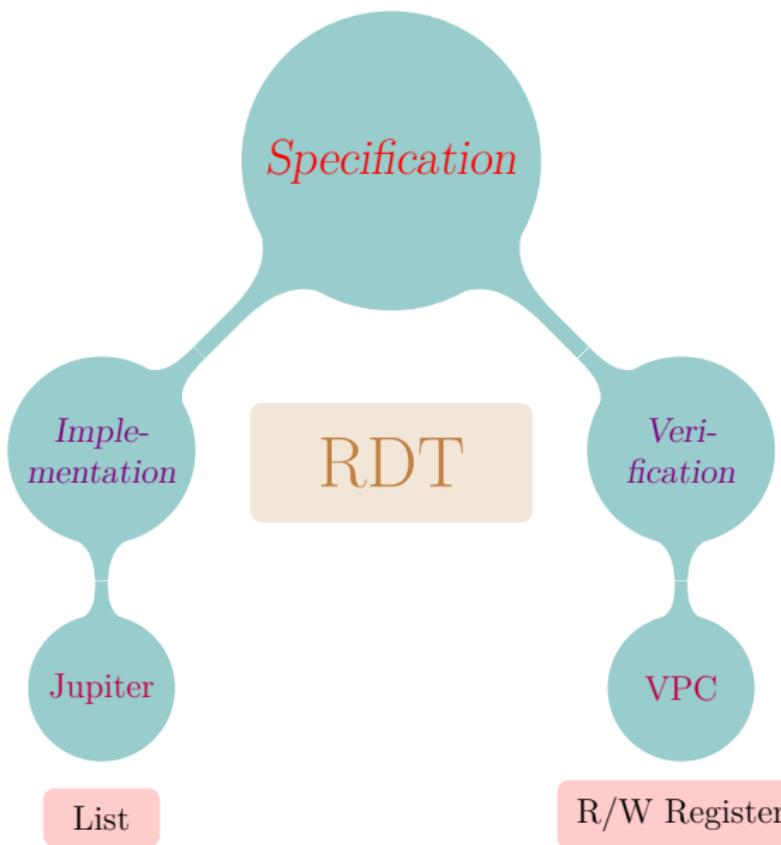
Hongseok Yang

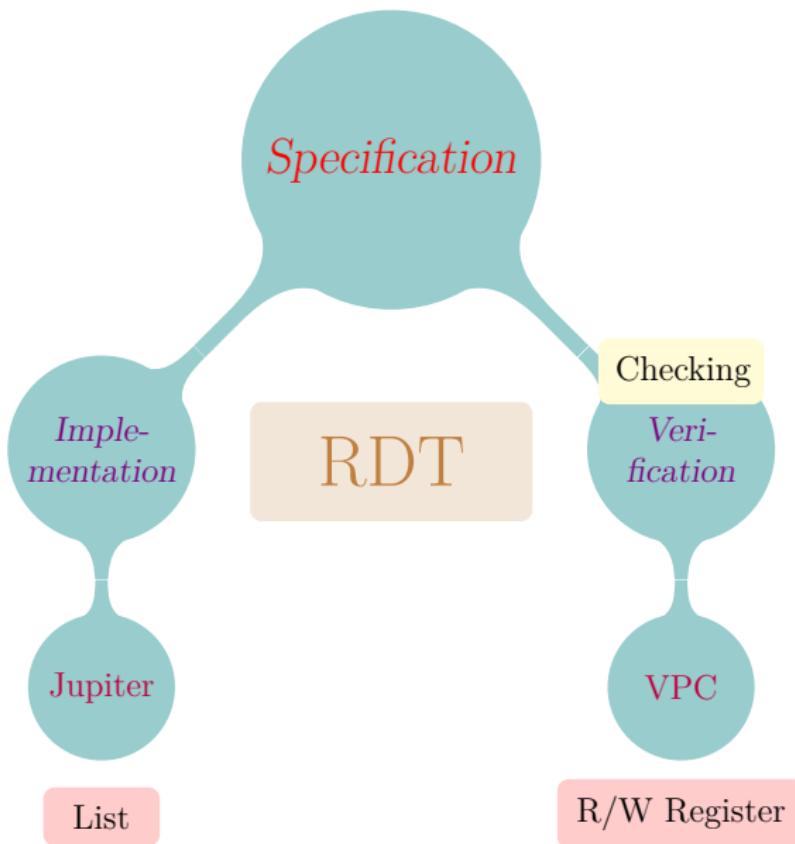
Marek Zawirski

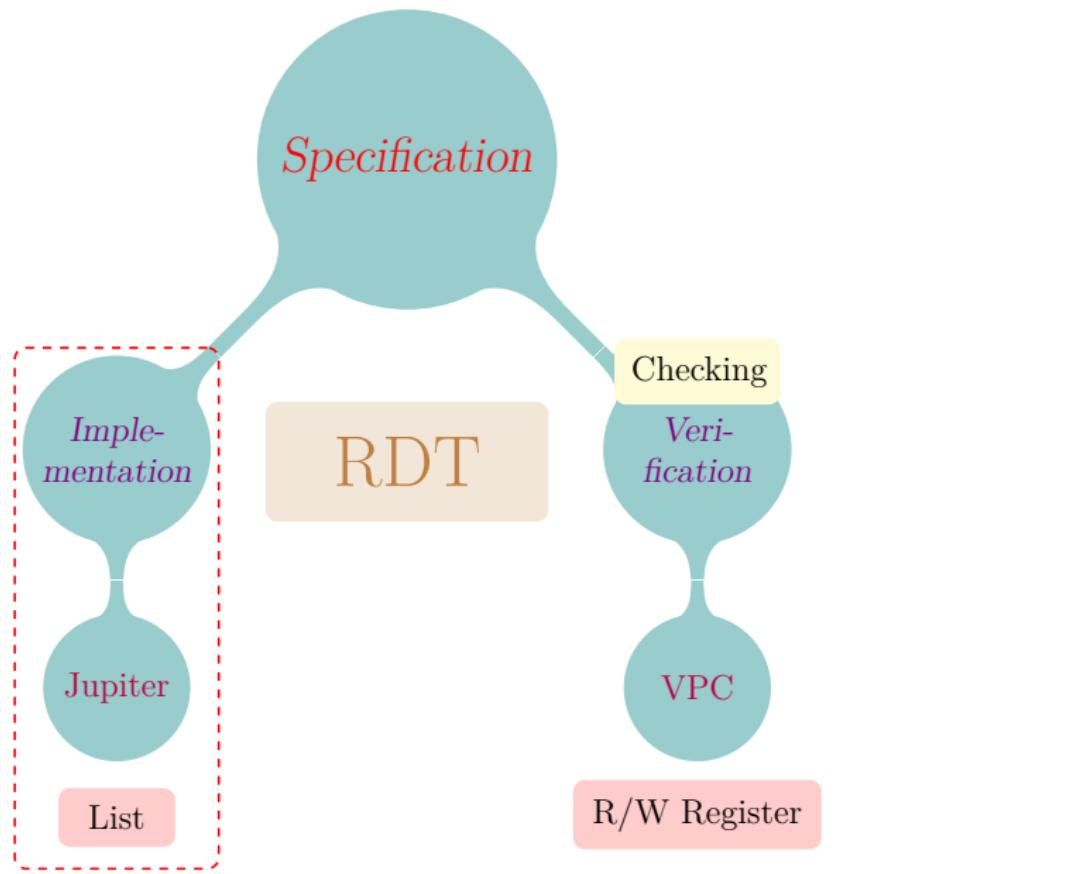
[Burckhardt et al., 2014]











Brief Announcement @ PODC'2018 ¹

实现复制列表的 Jupiter 协议 [Nichols et al., 1995]^a 满足
weak list specification [Attiya et al., 2016]^b.

^aDavid A. Nichols et al. (1995). “High-latency, Low-bandwidth Windowing in the Jupiter Collaboration System”. In: *Proceedings of the 8th Annual ACM Symposium on User Interface and Software Technology*. UIST '95. ACM, pp. 111–120.

^bHagit Attiya et al. (2016). “Specification and complexity of collaborative text editing”. In: *Proceedings of the 2016 ACM Symposium on Principles of Distributed Computing*. PODC '16. ACM, pp. 259–268.

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1 藏在脚注里的猜想@PODC'2016 [Attiya et al., 2016]

Weak List Specification

基于副本的协同文本编辑系统



(a) Google Docs



(b) Apache Wave



(c) Wikipedia



(d) LATEX Editor

复制列表对象: 建模编辑系统的核心功能

$\text{INS}(a, p)$: 在 p 位置插入元素 a

$\text{DEL}(p)$: 删除 p 位置上的元素

READ : 返回该列表

Specification and Complexity of Collaborative Text Editing

Hagit Attiya
Technion

Sebastian Burckhardt
Microsoft Research

Alexey Gotsman
IMDEA Software Institute

Adam Morrison
Technion

Hongseok Yang
University of Oxford

Marek Zawirski^{*}
Inria & Sorbonne Universités,
UPMC Univ Paris 06, LIP6

定义 (Weak List Specification $\mathcal{A}_{\text{weak}}$ [Attiya et al., 2016])

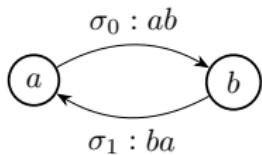
Informally, $\mathcal{A}_{\text{weak}}$ requires the ordering between elements that are not deleted to be consistent across the system.

定义在系统所有列表状态上的全局性质

定义 (状态对兼容性) (Pairwise State Compatibility Property)

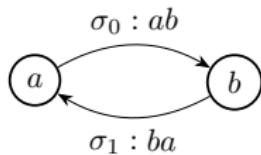
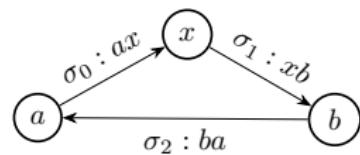
任给两个列表状态 σ_0 、 σ_1 , 若它们含有两个共同元素 a 、 b ,
则 a 、 b 在 σ_0 与 σ_1 中的相对顺序保持一致。

$$\boxed{\sigma_0 : ab} \quad \boxed{\sigma_1 : ba}$$



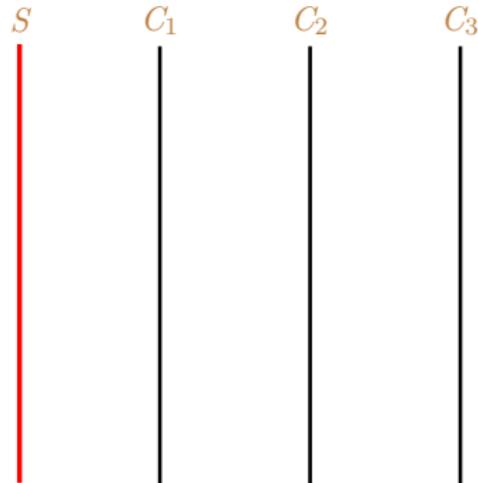
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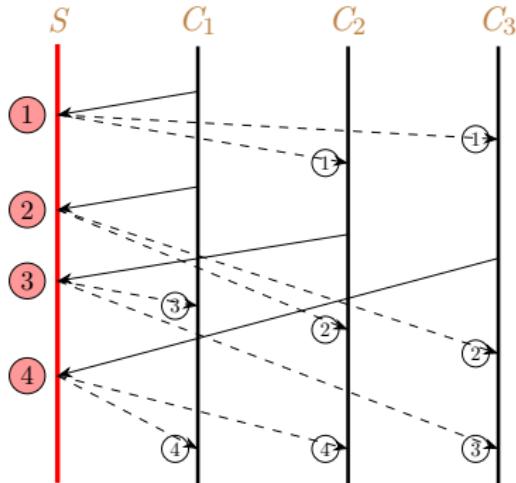
 $\sigma_0 : ab$ $\sigma_1 : ba$  $\sigma_0 : ax$ $\sigma_1 : xb$ $\sigma_2 : ba$ 

Jupiter

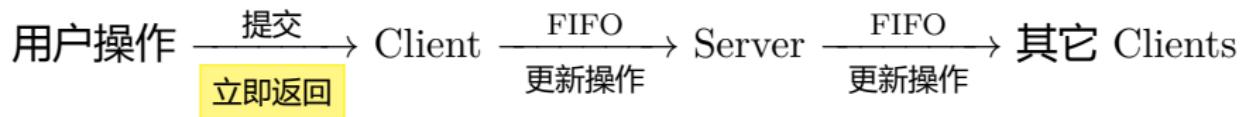
$(n + 1)$ replicas \triangleq (n) Client + (1) Server [Nichols et al., 1995]



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Server 负责将所有操作序列化

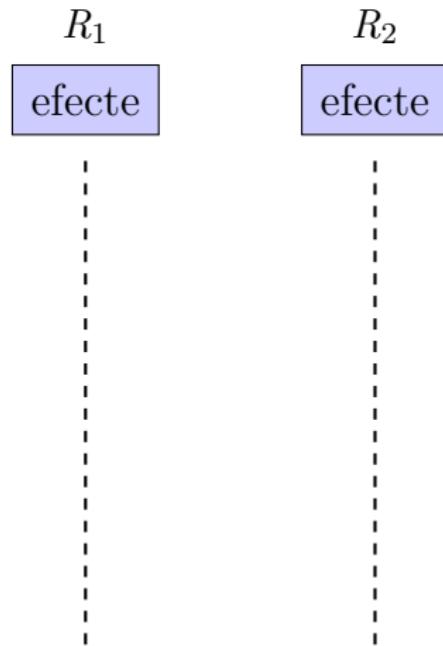


操作转换

(Operational Transformation; OT) [Ellis and Gibbs, 1989]

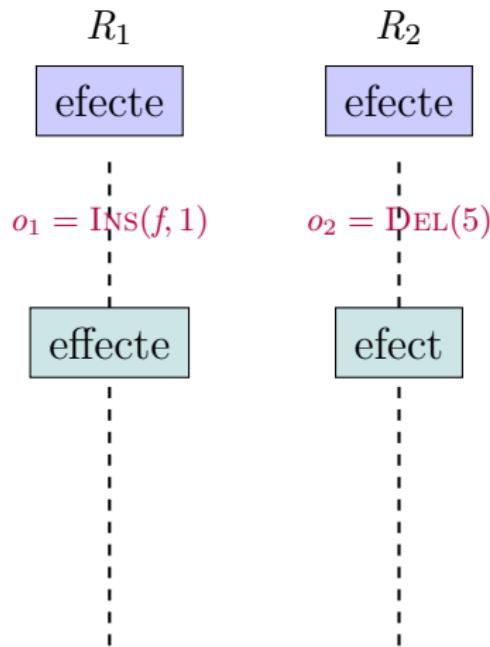
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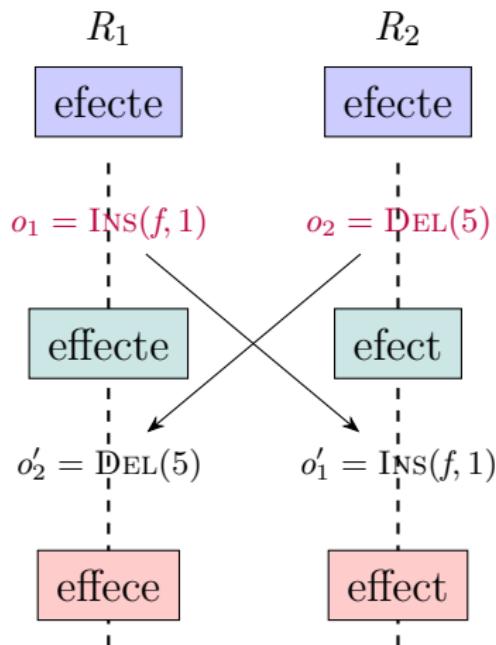
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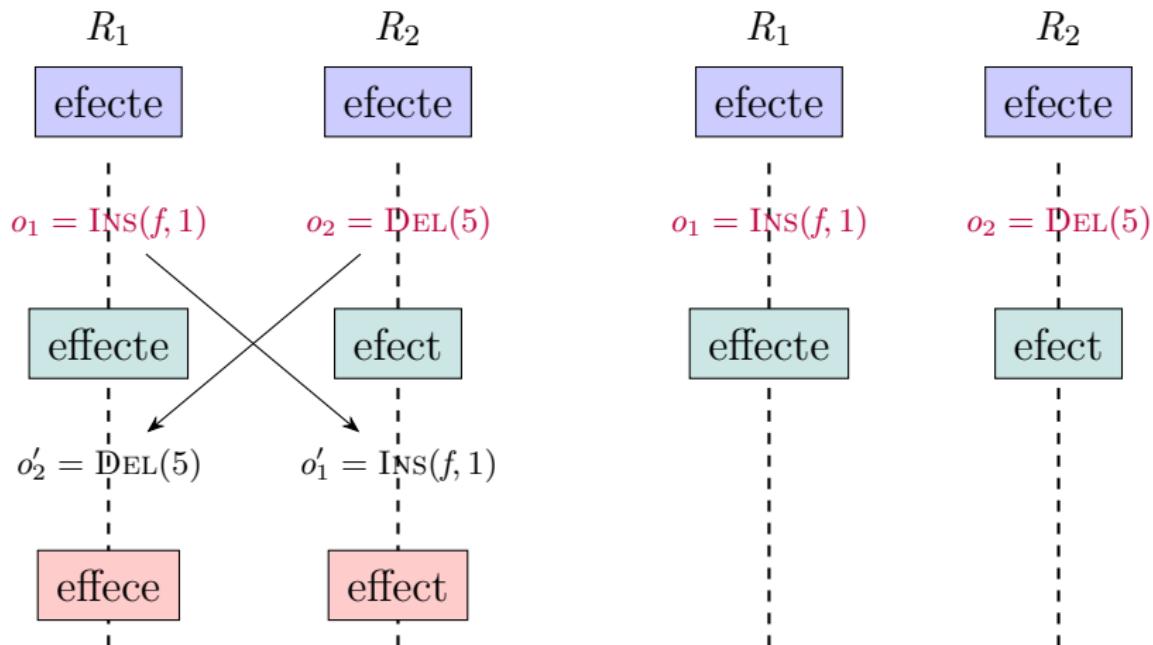
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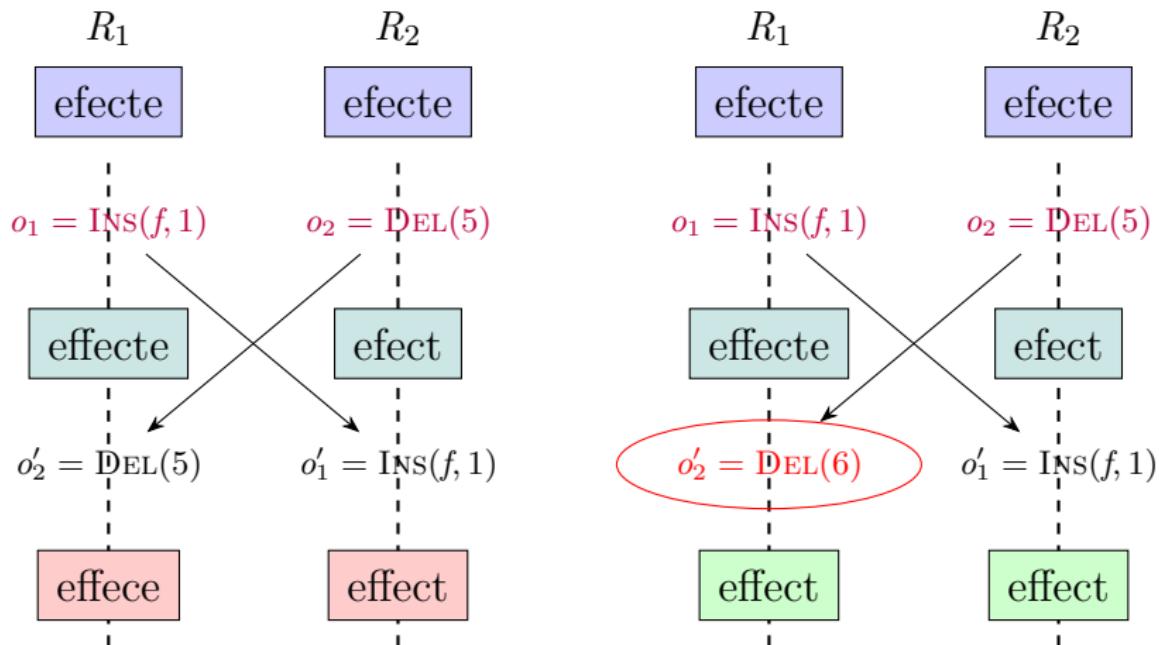
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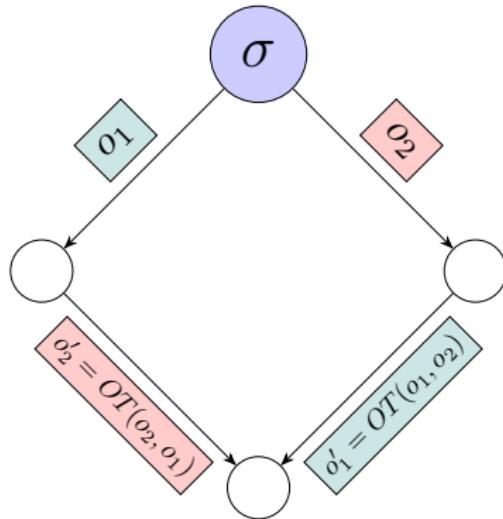
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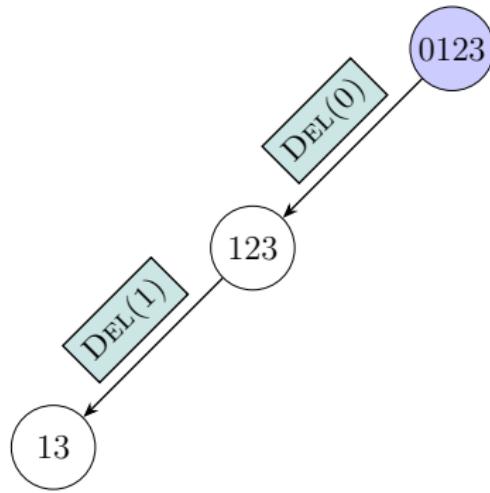
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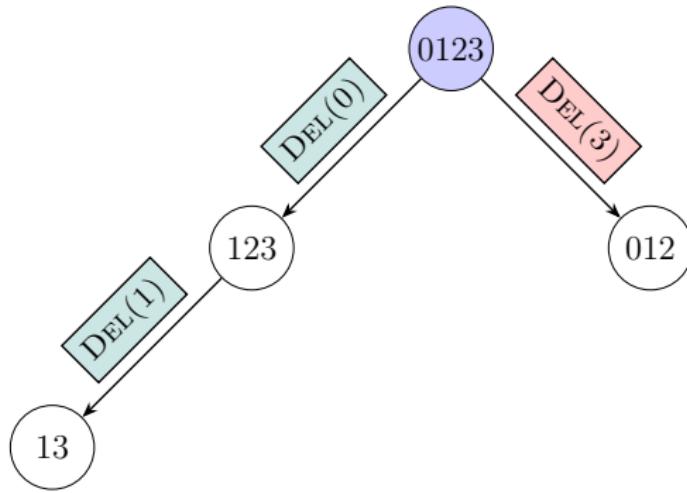


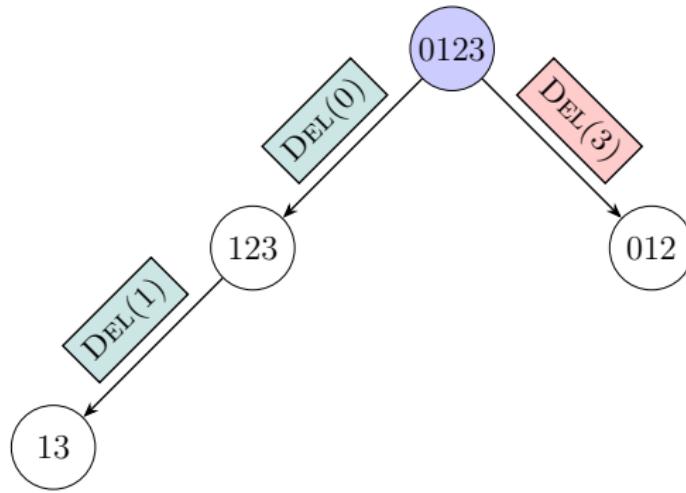


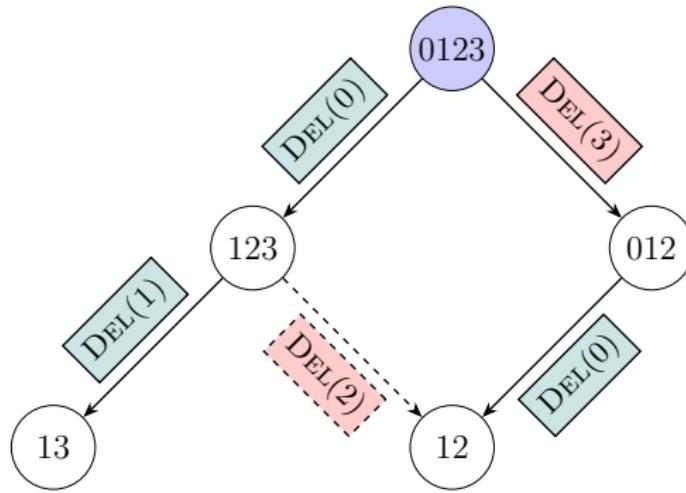
交换律 $\sigma; o_1; o'_2 \equiv \sigma; o_2; o'_1$

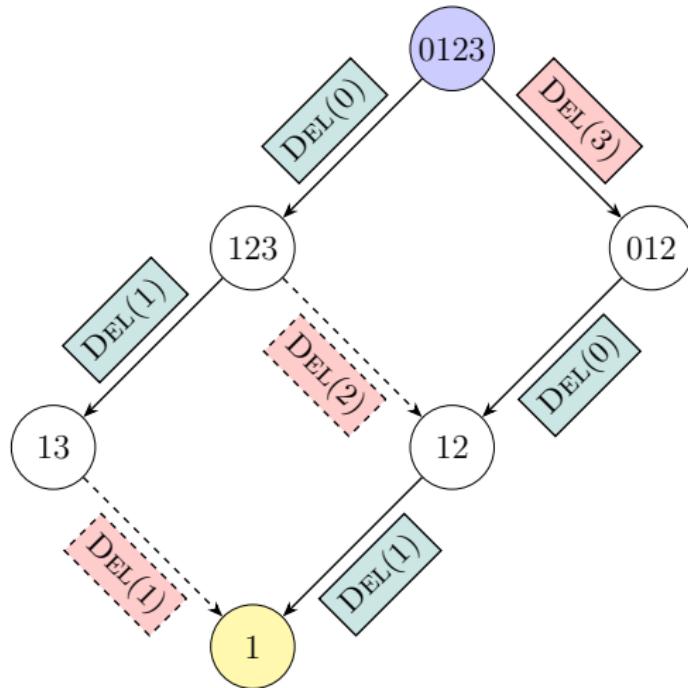
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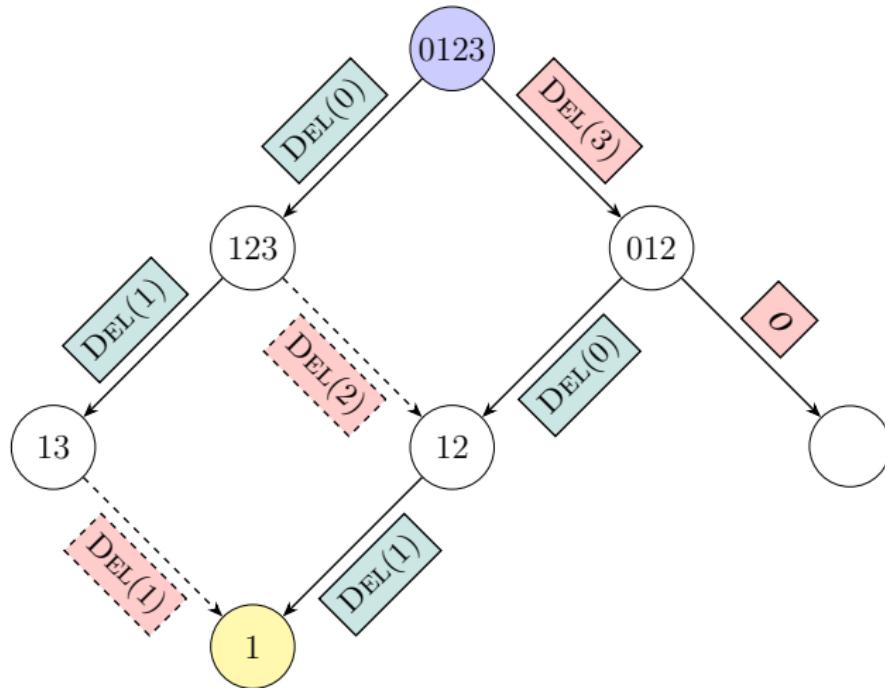






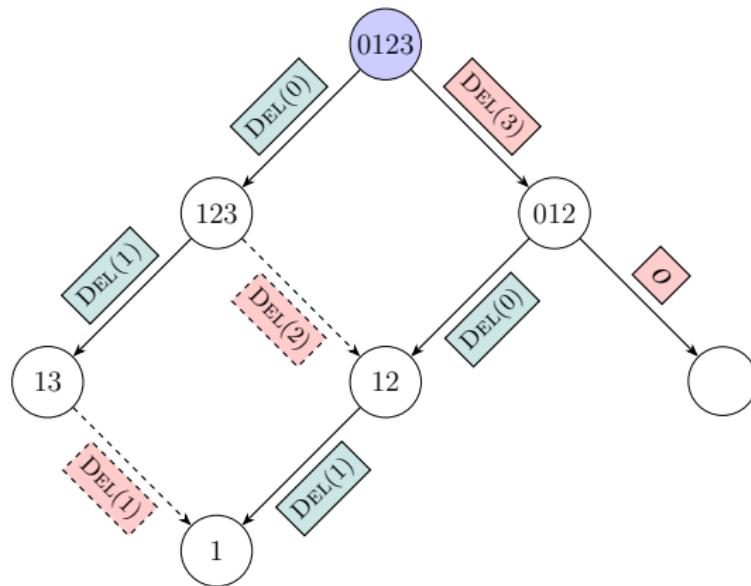






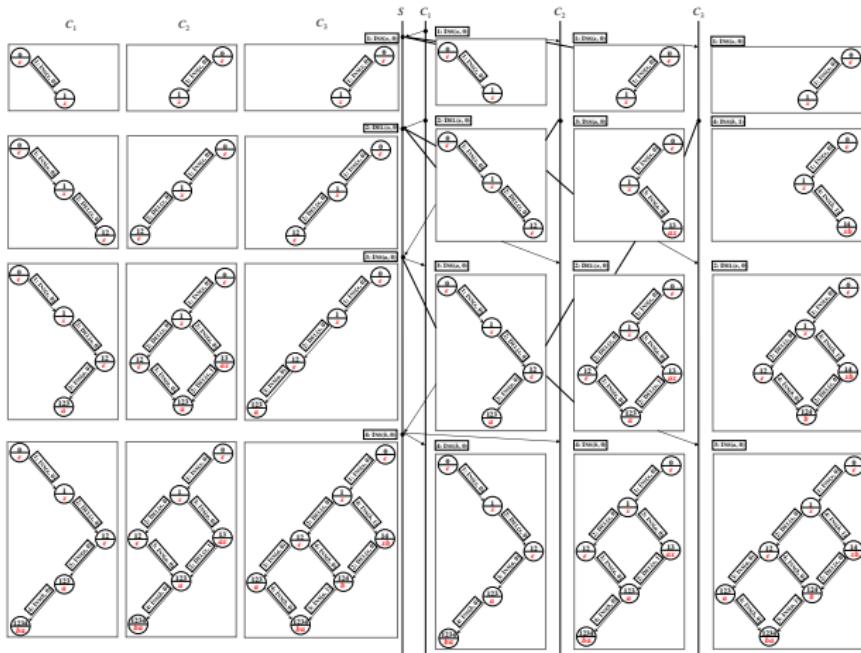
利用数据结构 2D 状态空间 [Xu, Sun, and Li, 2014]

控制何时以及如何执行“操作转换”



2D: LOCAL vs. GLOBAL

每个 Client 维护一个 2D 状态空间



Server 维护 n 个 2D 状态空间, 与 n 个 Clients 对应

Mismatch!

$\mathcal{A}_{\text{weak}}$ 所规定的全局性质



Jupiter 协议中, 每个 replica 所维护的局部视图

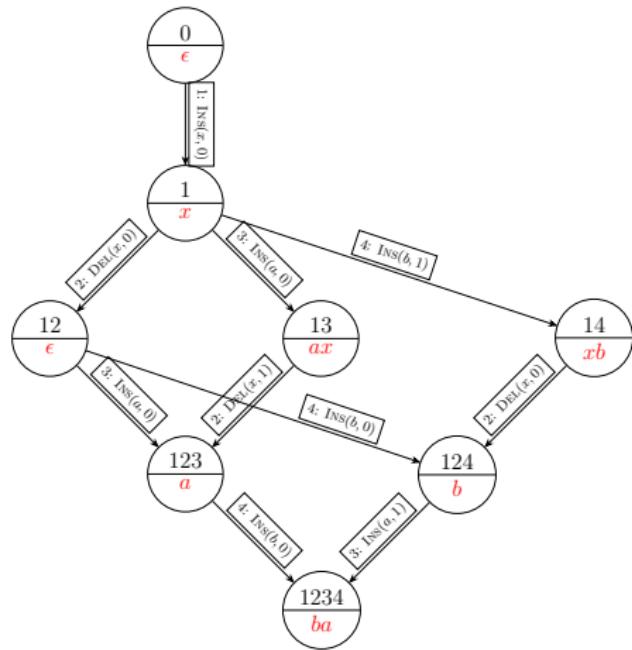
CJupiter (Compact Jupiter)

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定理 (等价性)

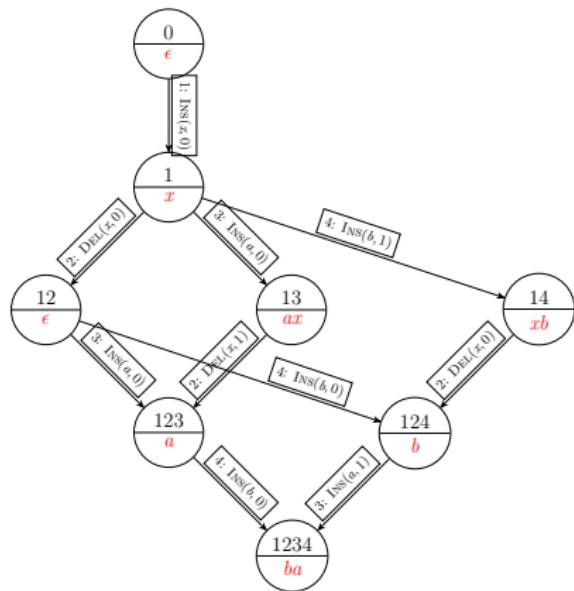
在相同的操作调度下, CJupiter 与 Jupiter 中的对应 *replica* 的行为 (状态序列) 是相同的。

CJupiter 为每个 replica 维护一个 ***n*-ary 有序状态空间**



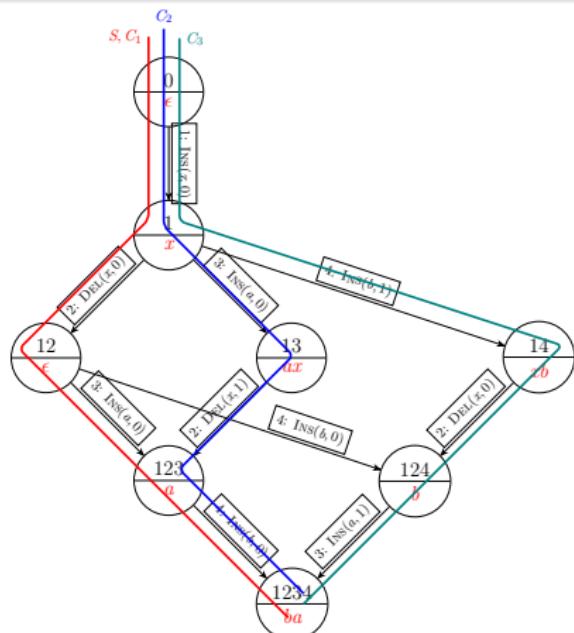
命题 (Compactness of CJupiter)

CJupiter 所维护的 $(n + 1)$ 个 n -ary 有序状态空间是相同的。



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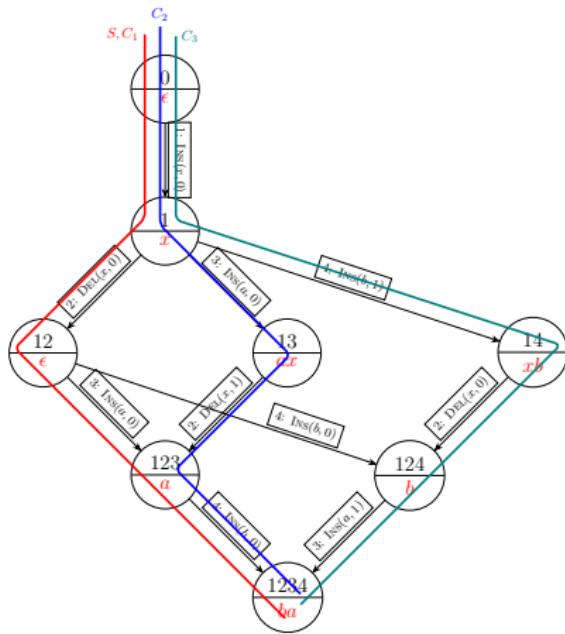
CJupiter 所维护的 $(n + 1)$ 个 n -ary 有序状态空间是相同的。



每个 replica 的行为对应于该状态空间中的一条 **路径**

CJupiter 满足 Weak List Specification

关注某个 n -ary 有序状态空间, 三步骤 证明“状态对兼容性”

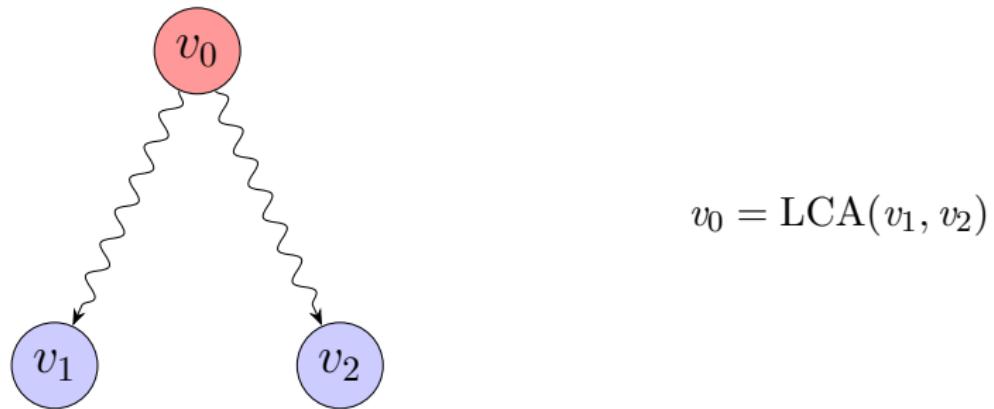


1

任取两个状态节点 v_1 和 v_2

引理 (LCA (Lowest Common Ancestor))

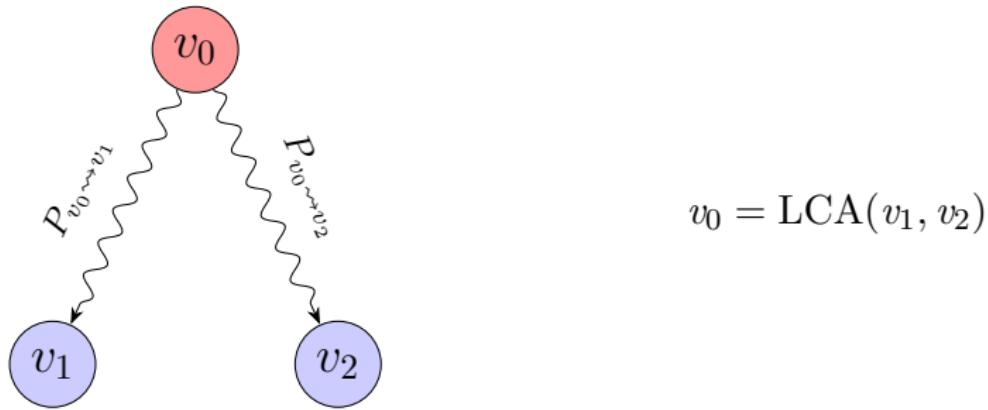
n -ary 有序状态空间中的任意一对状态节点都有唯一的最近公共祖先。



2 考虑从 $v_0 = \text{LCA}(v_1, v_2)$ 到 v_1 和 v_2 的两条路径

引理 (Disjoint Paths)

路径 $P_{v_0 \rightsquigarrow v_1}$ 上包含的操作集 $O_{v_0 \rightsquigarrow v_1}$ 与路径 $P_{v_0 \rightsquigarrow v_2}$ 上包含的操作集 $O_{v_0 \rightsquigarrow v_2}$ 不相交。

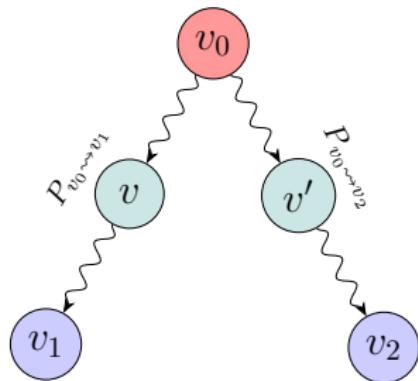


3

考虑两条路径上的状态

引理 (Compatible Paths)

$P_{v_0 \rightsquigarrow v_1}$ 上的任一状态 v 与 $P_{v_0 \rightsquigarrow v_2}$ 上的任一状态 v' 是兼容的。



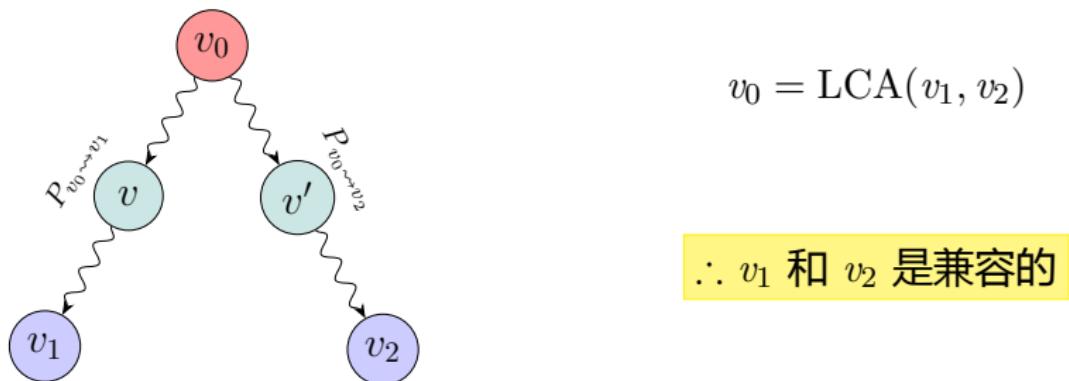
$$v_0 = \text{LCA}(v_1, v_2)$$

3

考虑两条路径上的状态

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个人体会: 基于 OT 思想的协议晦涩难懂



个人体会: 基于 OT 思想的协议晦涩难懂



- ▶ 协议多种多样
- ▶ 经常不加证明
- ▶ 证明是错误的

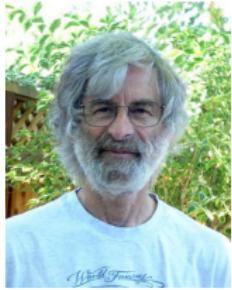
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- ▶ **勘误也是错的**

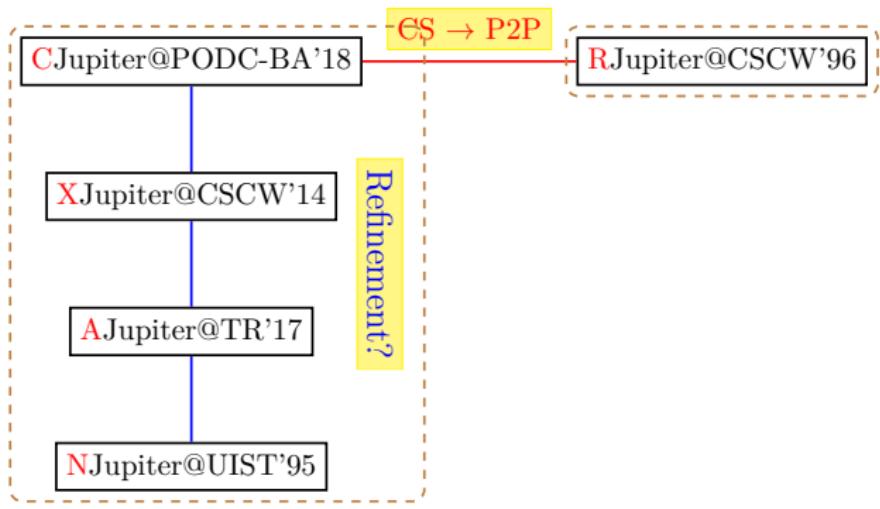
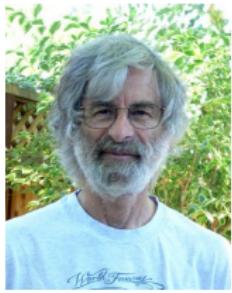
Model Checking: 使用 TLA+

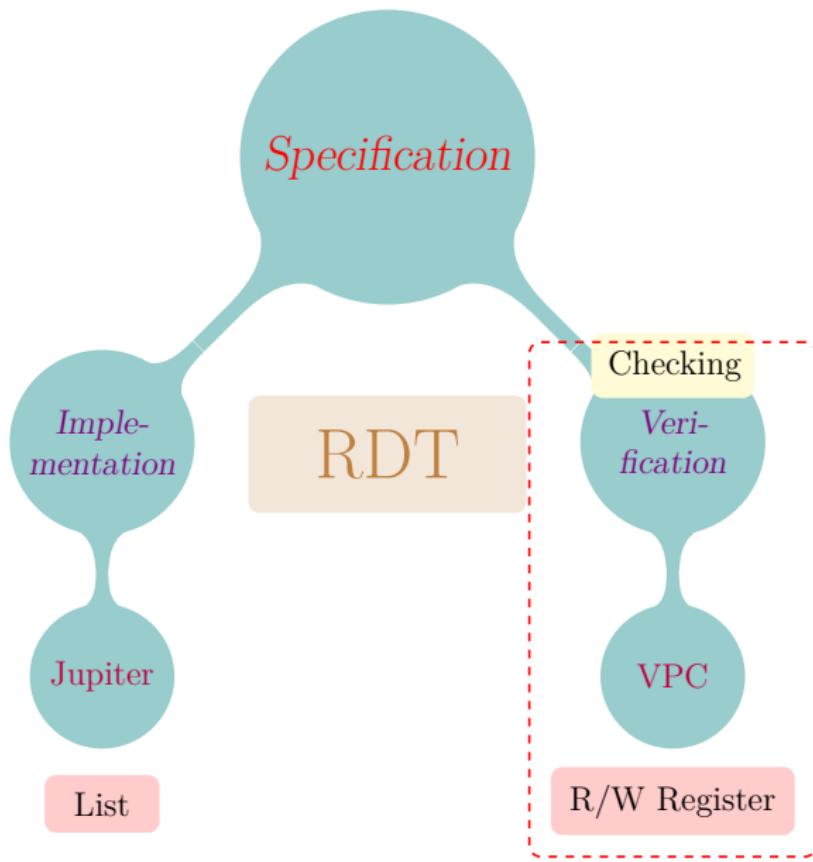
jupiter-tlaplus@github



Model Checking: 使用 TLA+

jupiter-tlaplus@github





协议验证 (Verification of a Protocol)

执行验证 (Verification of an Execution)

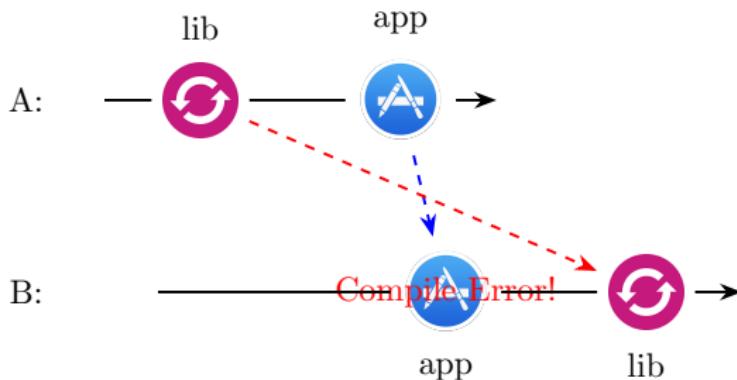
协议验证 (Verification of a Protocol)

执行验证 (Verification of an Execution)



黑盒测试/确认系统是否提供了其所声称的数据一致性
[DeCandia et al., 2007] [Golab, Li, and Shah, 2011]

PRAM: 包含存储系统常提供的最基本的“会话”(session)一致性
[Terry et al., 1994] [Brzezinski, Sobaniec, and Wawrzyniak, 2004]



PRAM 保证“单调写”性质

定义 (VPC (Verifying PRAM Consistency) 判定问题)

实例: 系统执行 (*execution e*)

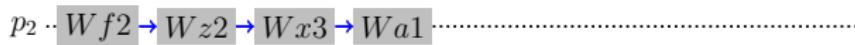
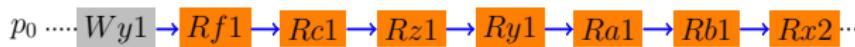
问题: 该执行 e 是否满足 PRAM 一致性模型 (\mathcal{C})?

$$e \in \mathcal{C} \Rightarrow \{0, 1\}?$$

定义 (系统执行)

系统执行 $e \triangleq \{h_p \mid h_p : \text{进程 } p \text{ 上的读写操作序列}\}$

规模 n : 系统执行中读写操作的总数

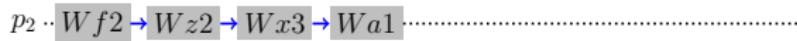
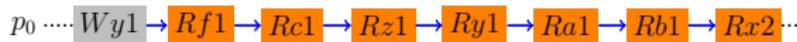


定义 (PRAM 一致性模型)

系统执行 e 满足 PRAM 一致性



$\forall p : p$ 上所有操作与其它进程上所有写操作存在合法调度

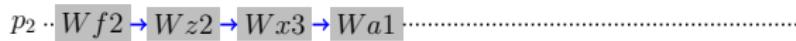
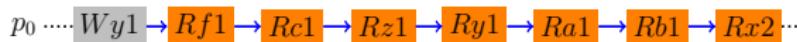


定义 (PRAM 一致性模型)

系统执行 e 满足 PRAM 一致性

1

$\forall p : p$ 上所有操作与其它进程上所有写操作存在合法调度



$p_0 : Wf2\ Wf1\ Wz2\ Wz1\ Wy2\ Wy1\ Rf1\ Wx5\ Wx3\ Wx2\ Wc1\ Rcl$
 $Rz1\ Ry1\ Wa1\ Ra1\ Wb1\ Rb1\ Rx2$

VPC 问题的四种变体 (按“执行”的类型) 及复杂度
([*] : 本文工作)

	<i>(S)ingle variable</i>	<i>(M)ultiple variables</i>
<i>write (D)uplicate values</i>	VPC-SD	VPC-MD
<i>write (U)nique value</i>	VPC-SU	VPC-MU

VPC 问题的四种变体 (按“执行”的类型) 及复杂度
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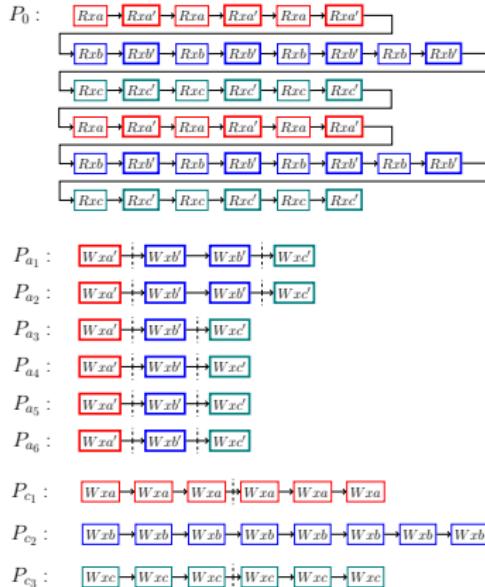
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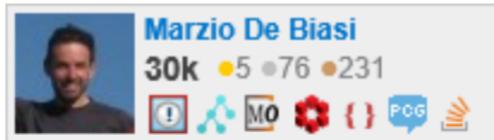
Read-mapping [Gibbons and Korach, 1997]: $\forall r, \exists! w, f(r) = w.$

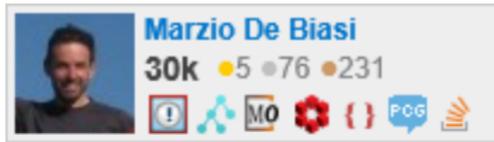
VPC-SD (VPC-MD) 是 NP-complete 问题

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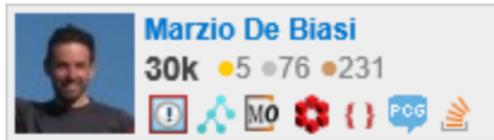


UNARY 3-PARTITION 实例 $A = \{2, 2, 1, 1, 1, 1\}$, $m = 2$, $B = 4$ 对应的 VPC-SD 执行



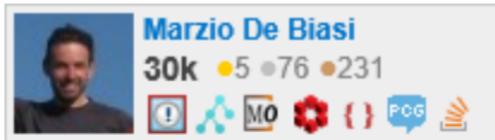


“Basically I'm a programmer :-)



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*I enjoy reading papers about the complexity of puzzle games,
and I'm writing (amateur) proofs on the complexity of a few
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VPC-MU 的多项式算法 RW-CLOSURE

→ program order → write-to order → w'wr order

$p_0 \dots W_{y1} Rf1 Rc1 Rz1 Ry1 Ra1 Rb1 Rx2 \dots$

$p_1 \dots Wf1 Wx2 Wc1 \dots$

$p_2 \dots Wf2 Wz2 Wx3 Wa1 \dots$

$p_3 \dots Wz1 Wy2 Wx5 Wb1 \dots$

RW-CLOSURE 算法示例: 在传递闭包之上迭代应用 $w'wr$ 规则

VPC-MU 的多项式算法 RW-CLOSURE

→ program order → write-to order → w'wr order

$p_0 \dots W_{y1} \rightarrow R_{f1} \rightarrow R_{c1} \rightarrow R_{z1} \rightarrow R_{y1} \rightarrow R_{a1} \rightarrow R_{b1} \rightarrow R_{x2} \dots$

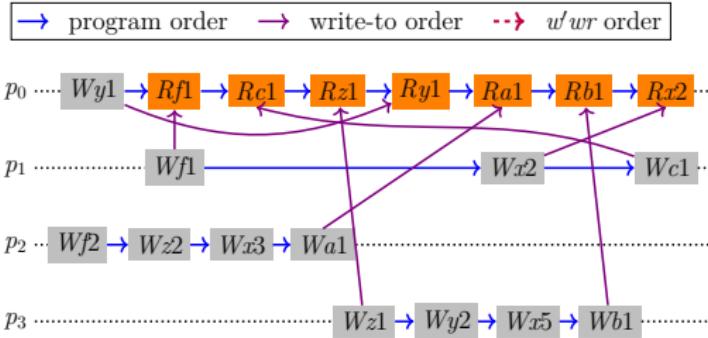
$p_1 \dots \dots \dots W_{f1} \xrightarrow{\quad} W_{x2} \xrightarrow{\quad} W_{c1} \dots$

$p_2 \dots W_{f2} \rightarrow W_{z2} \rightarrow W_{x3} \rightarrow W_{a1} \dots \dots \dots$

$p_3 \dots \dots \dots W_{z1} \rightarrow W_{y2} \rightarrow W_{x5} \rightarrow W_{b1} \dots \dots \dots$

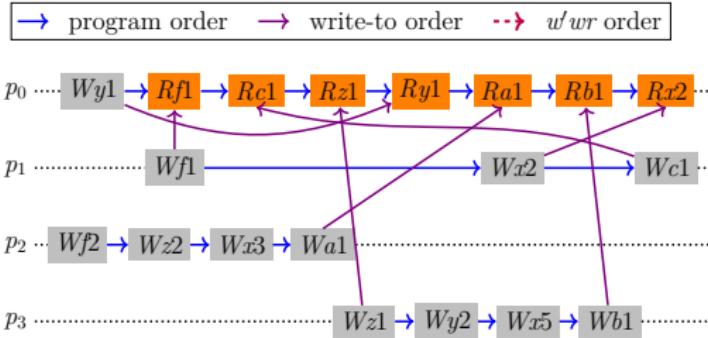
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VPC-MU 的多项式算法 RW-CLOSURE

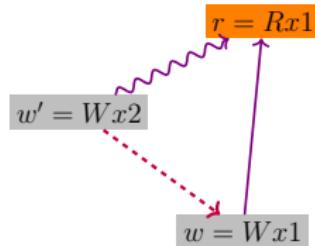


RW-CLOSURE 算法示例: 在传递闭包之上迭代应用 $w' wr$ 规则

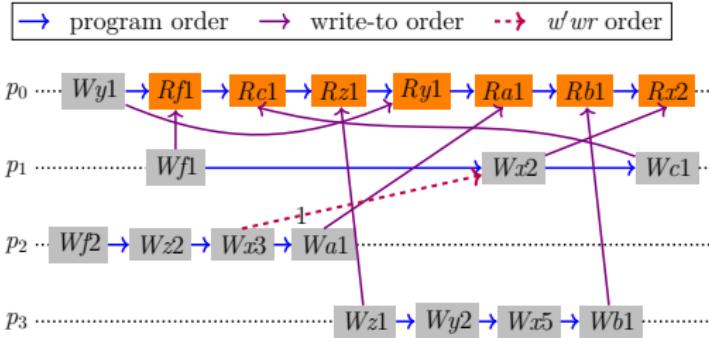
VPC-MU 的多项式算法 RW-CLOSURE



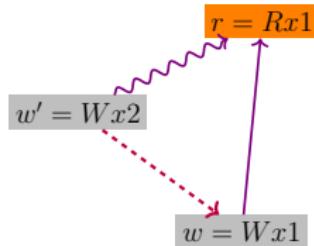
RW-CLOSURE 算法示例：在传递闭包之上迭代应用 $w' wr$ 规则



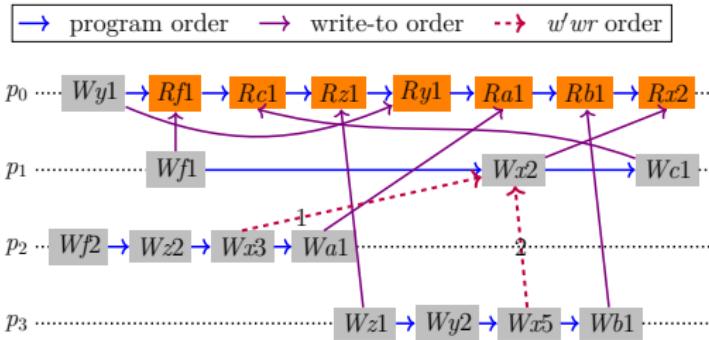
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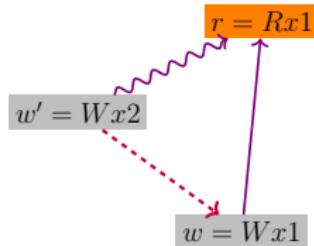
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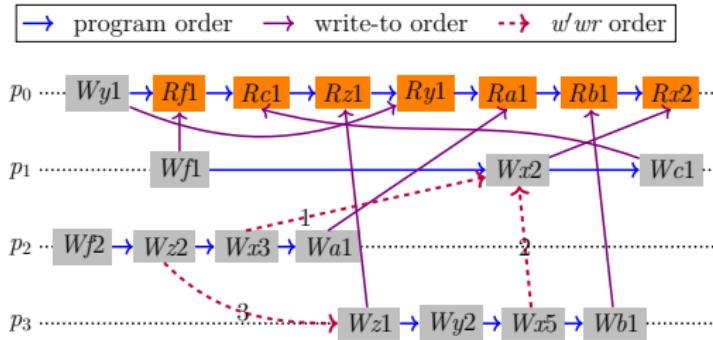
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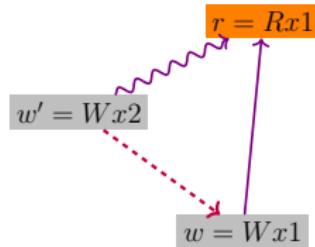
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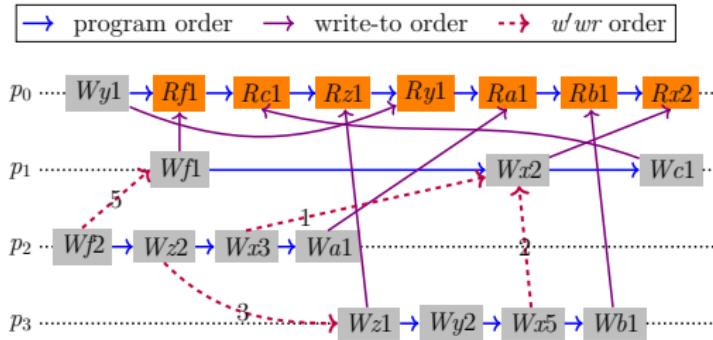
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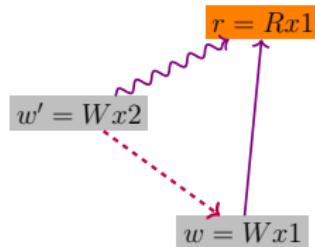
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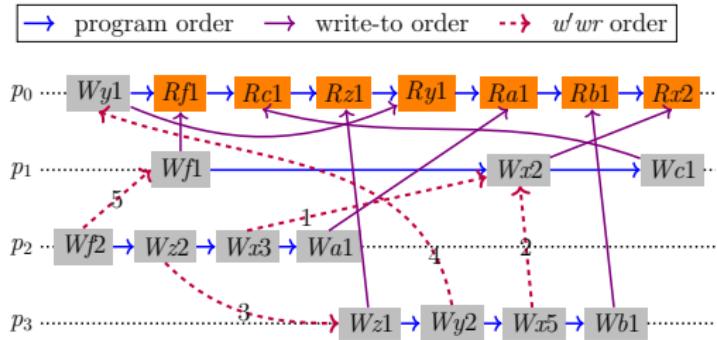
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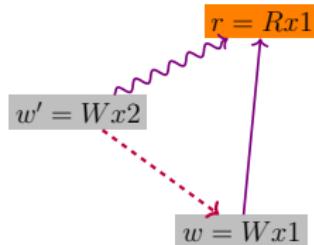
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VPC-MU 的多项式算法 RW-CLOSURE



RW-CLOSURE 算法示例: 在传递闭包之上迭代应用 $w' wr$ 规则



定理 (RW-CLOSURE 算法正确性)

VPC-MU 实例满足 PRAM 一致性



RW-CLOSURE 算法所得图是 DAG 图

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证明

“ \implies ” 反证法

“ \impliedby ” 对读操作作数学归纳，构造合法调度

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“ \implies ” 反证法

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RW-CLOSURE 算法复杂度：

$$\underbrace{O(n^2)}_{\# \text{loops}} \cdot \underbrace{O(n^3)}_{\text{transitive closure}} = O(n^5)$$

RW-CLOSURE 算法的缺点:

- ▶ 在全图上应用 $w'wr$ 规则
- ▶ 应用 $w'wr$ 规则无特定顺序

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VPC-MU 的多项式算法 READ-CENTRIC 要点:

- ▶ 增量式调度每个读操作
- ▶ 在读操作诱导的局部子图上按逆拓扑序应用 $w'wr$ 规则

定理 (READ-CENTRIC 算法正确性)

VPC-MU 实例满足 PRAM 一致性



READ-CENTRIC 算法所得图是 DAG 图

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READ-CENTRIC 算法所得图是 DAG 图

证明

READ-CENTRIC $\xleftrightarrow{\text{Reachability}}$ RW-CLOSURE

定理 (READ-CENTRIC 算法正确性)

VPC-MU 实例满足 PRAM 一致性



READ-CENTRIC 算法所得图是 DAG 图

证明

$$\text{READ-CENTRIC} \iff^{\text{Reachability}} \text{RW-CLOSURE}$$

READ-CENTRIC 算法复杂度:

$$\underbrace{O(n)}_{\# \text{ reads}} \cdot \underbrace{O(n \cdot n^2)}_{\text{TOPO-SCHEDULE}} = O(n^4)$$

VPC 在相关工作中的意义

较早关注 (分布式系统领域) “弱一致性模型验证” 问题 (2013~):

强一致性: [Gibbons and Korach, 1997] [Cantin, Lipasti, and Smith, 2005] [Golab, Li, and Shah, 2011]

弱一致性: [Furbach et al., 2014] [Bouajjani et al., 2017]
[Emmi and Enea, 2018]

VSC (Verifying Sequential Consistency) 与 VL (Verifying Linearizability)
问题的复杂度 [Gibbons and Korach, 1997]

Variants	VSC	VL
General	NP-complete	NP-complete
2 Operations/Process	NP-complete	NP-complete
2 Variables	NP-complete	NP-complete
3 Processes	NP-complete	$O(n \log n)$
Read-mapping	NP-complete	$O(n \log n)$
Write-order	NP-complete	$O(n \log n)$
read&write only	NP-complete	NP-complete
Conflict-order	$O(n \log n)$	$O(n \log n)$

VMC (Verifying Memory Coherence) 问题的复杂度 [Cantin, Lipasti, and Smith, 2005]

Variants	Read/Write	Read-Modify-Write
1 Operation/Process	$O(n \lg n)$	$O(n^2)$
2 Operations/Process	?	NP-complete
3+ Operations/Process	NP-complete	NP-complete
Constant k processes	$O(n^k)$	$O(n^k)$
1 Write/Value (Read-mapping)	$O(n)$	$O(n \lg n)$
2 Writes/Value	NP-complete	?
3+ Writes/Value	NP-complete	NP-complete
Write-order	$O(n^2)$	$O(n)$

Atomicity² 相关一致性模型验证问题复杂度 (假设: 不允许写重复值)

	Safety	Regularity	Atomicity	Sequential
Offline [Anderson et al., 2010]	$O(n^2)$	$O(n^2)$	$O(n^3)$	<i>not studied</i>
Online³ [Golab, Li, and Shah, 2011]	$O(n)$	$O(n)$	$O(n \log n)$	$\text{Poly}(n)$

²也称 Linearizability

³包含其它假设

k -AV (k -Atomicity Verification) 问题复杂度

Problems	Variants	Results	Work
1-AV	General	NP-complete	[Gibbons and Korach, 1997]
1-AV	Write unique value	$O(n \log n)$	[Gibbons and Korach, 1997]
2-AV	Write unique value	$O(n \log n)$	[Golab, Hurwitz, and Li, 2013]
k -AV	Write unique value	$O(n^2)$	[Golab et al., 2015]
	Bounded concurrency		[Golab et al., 2018]
k -AV	Write unique value		

k -AV (k -Atomicity Verification) 问题复杂度

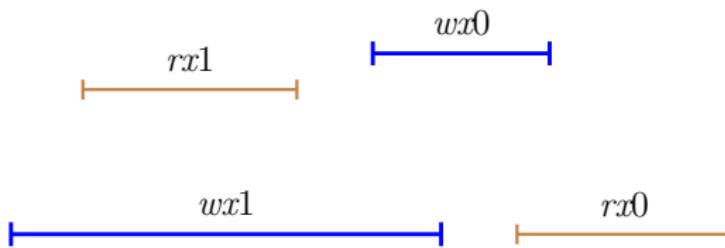
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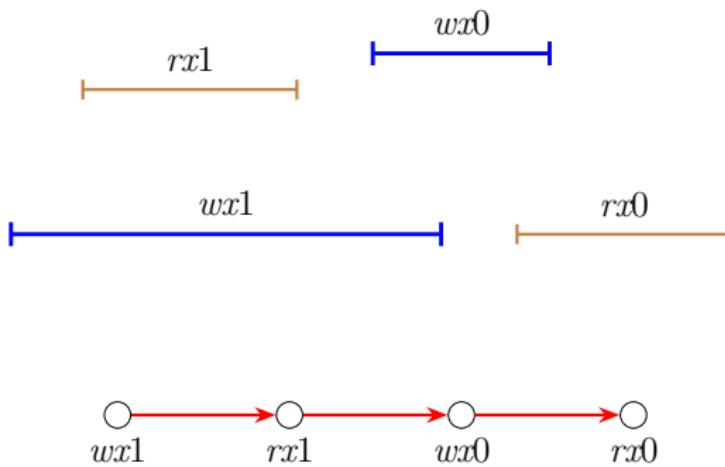
Atomicity = 实时序 + 读写语义

[Lamport, 1986]



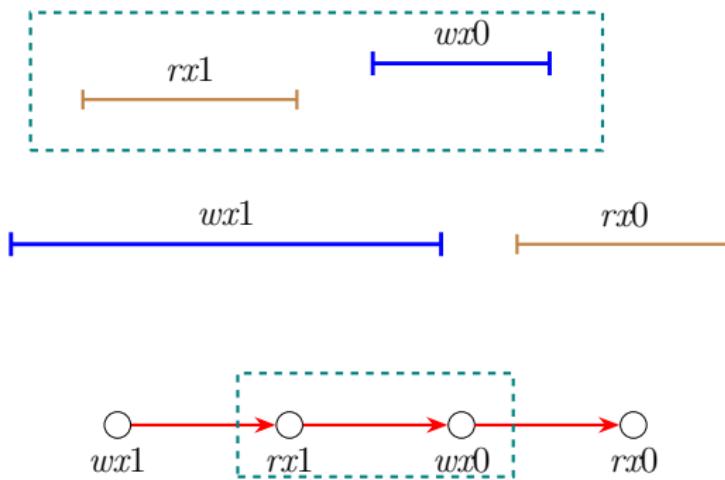
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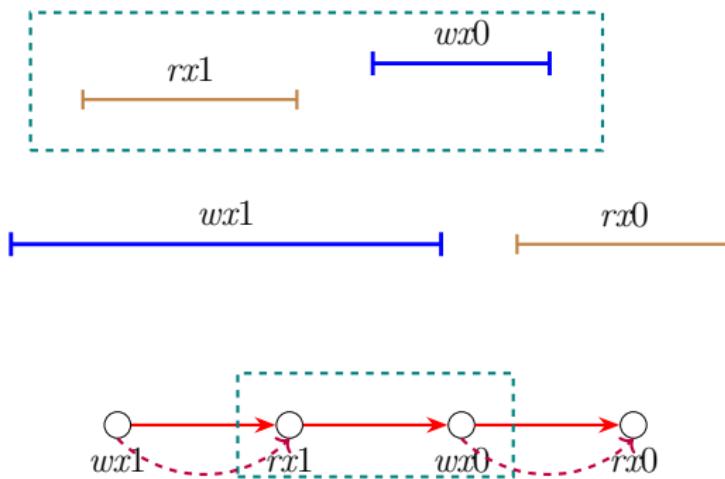
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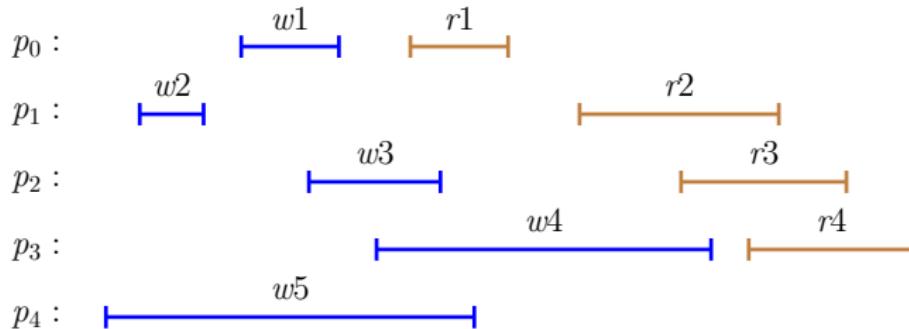
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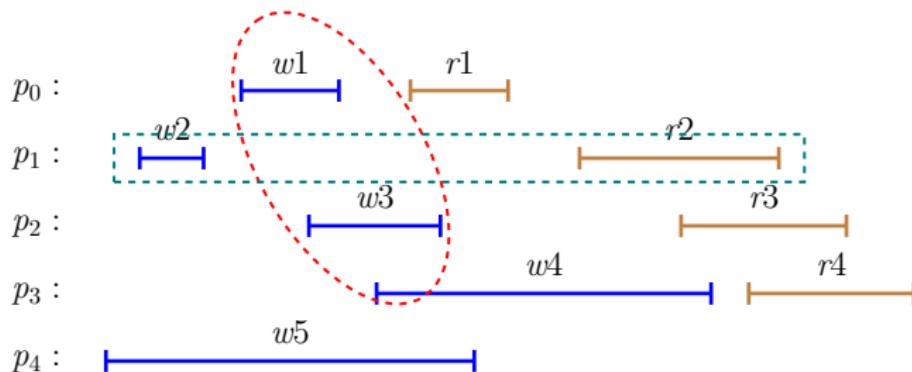
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[Aiyer, Alvisi, and Bazzi, 2005] [Taubenfeld, 2013]



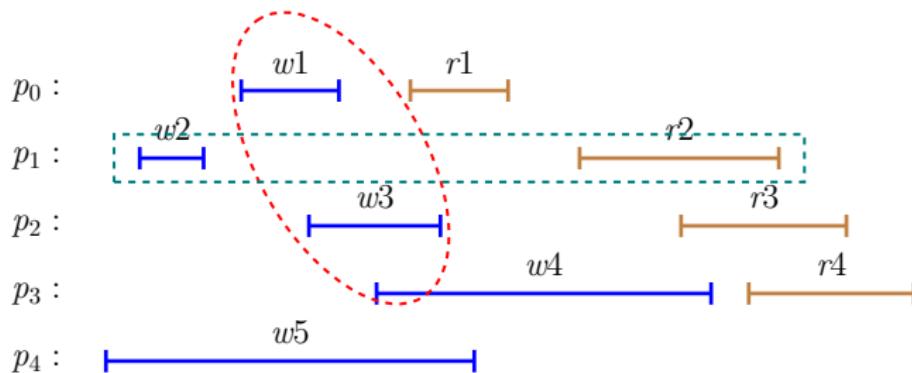
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3-Atomicity : $w5 \quad \textcolor{red}{w2} \quad w1 \quad r1 \quad w3 \quad w4 \quad \textcolor{red}{r2} \quad r3 \quad r4$

定义 (k -AV (k -Atomicity Verification) 判定问题)

实例: 系统执行 e (不允许写重复值)、参数 k

问题: 该执行 e 是否满足 k -Atomicity?





协议量化分析

[Lee and Welch, 2005] [Bailis et al., 2012] [Chatterjee and Golab, 2017]

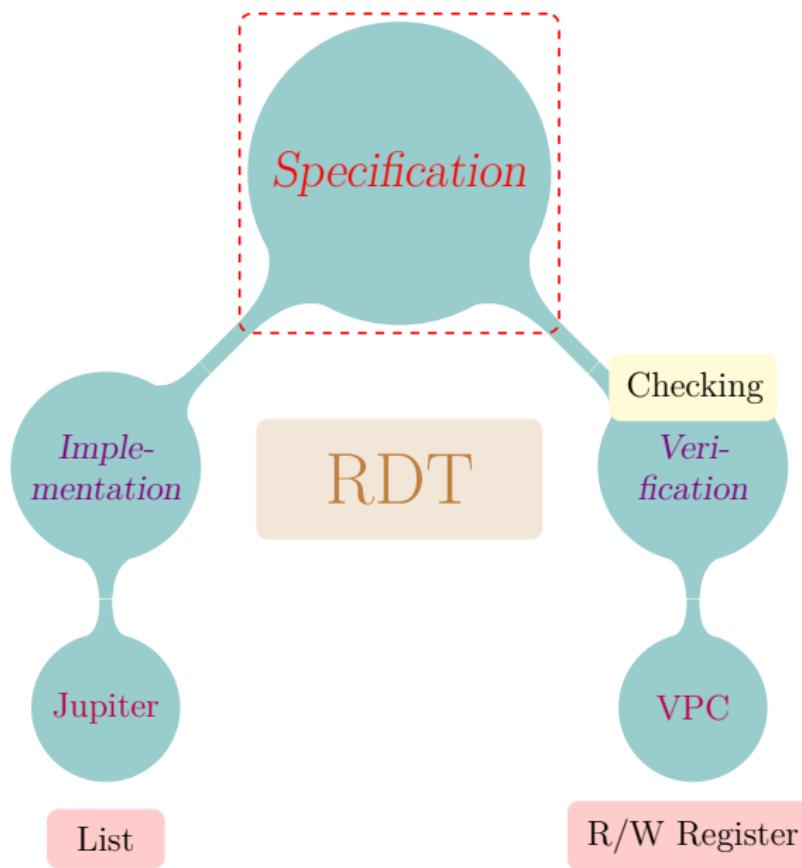


协议量化分析

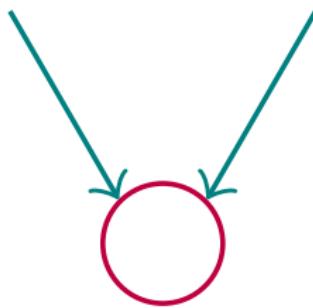
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PA2AM: Probabilistically-Atomic 2-Atomicity

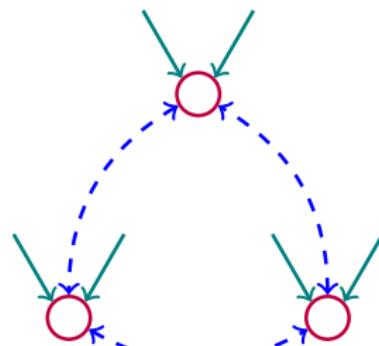




多处理器系统中的并发数据类型

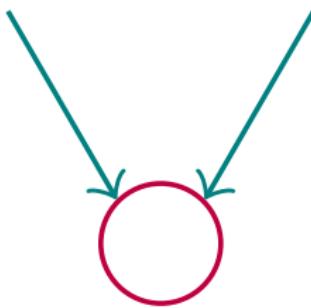


分布式系统中的复制数据类型

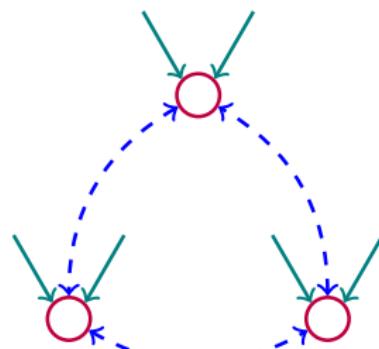


规约: 数据一致性模型 (Consistency Model)

多处理器系统中的并发数据类型

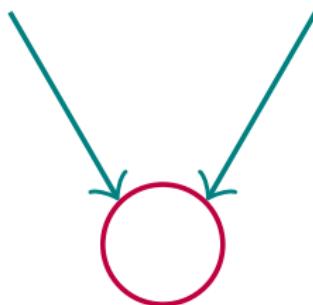


分布式系统中的复制数据类型



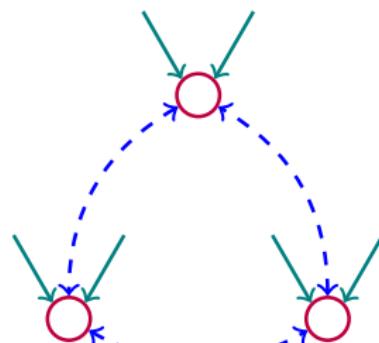
规约: 数据一致性模型 (Consistency Model)

多处理器系统中的并发数据类型



PL + DC

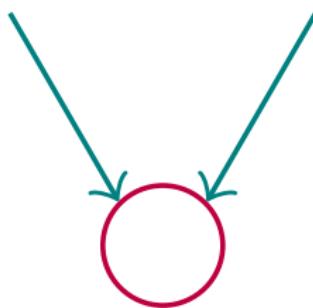
分布式系统中的复制数据类型



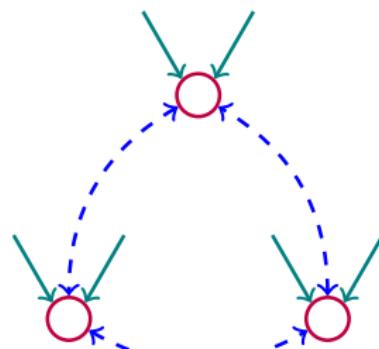
[Burckhardt et al., 2014]

规约: 数据一致性模型 (Consistency Model)

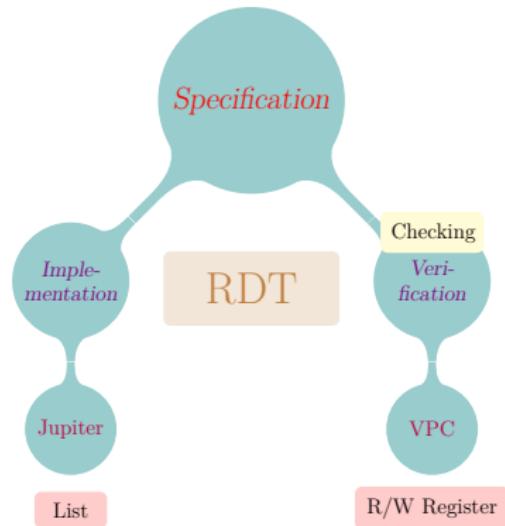
多处理器系统中的并发数据类型



分布式系统中的复制数据类型



PL + DC + FM [Burckhardt et al., 2014]



Thank You!

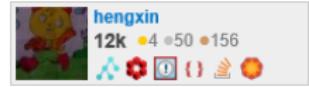
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-  Aiyer, Amitanand, Lorenzo Alvisi, and Rida A. Bazzi (2005). "On the Availability of Non-strict Quorum Systems". In: *Proceedings of the 19th International Conference on Distributed Computing*. DISC '05. Springer-Verlag, pp. 48–62.
-  Anderson, Eric et al. (2010). "What Consistency Does Your Key-value Store Actually Provide?" In: *Proceedings of the Sixth International Conference on Hot Topics in System Dependability*. HotDep'10. Vancouver, BC, Canada: USENIX Association, pp. 1–16. URL:
<http://dl.acm.org/citation.cfm?id=1924908.1924919>.
-  Attiya, Hagit et al. (2016). "Specification and complexity of collaborative text editing". In: *Proceedings of the 2016 ACM Symposium on Principles of Distributed Computing*. PODC '16. ACM, pp. 259–268.
-  Bailis, Peter et al. (2012). "Probabilistically Bounded Staleness for Practical Partial Quorums". In: *Proc. VLDB Endow.* 5.8, pp. 776–787.
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定义 (最终收敛性 (Eventual Convergence) [Ellis and Gibbs, 1989])

当用户不再提交更新操作时, 所有 *replicas* 上的列表是相同的。

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对系统的中间状态缺少足够的约束

针对列表的操作转换函数 [Ellis and Gibbs, 1989]

$$OT\left(\text{INS}(a_1, p_1, pr_1), \text{INS}(a_2, p_2, pr_2) \right) = \begin{cases} \text{INS}(a_1, p_1, pr_1) & p_1 < p_2 \\ \text{INS}(a_1, p_1 + 1, pr_1) & p_1 > p_2 \\ \text{NOP} & p_1 = p_2 \wedge a_1 = a_2 \\ \text{INS}(a_1, p_1 + 1, pr_1) & p_1 = p_2 \wedge a_1 \neq a_2 \wedge pr_1 > pr_2 \\ \text{INS}(a_1, p_1, pr_1) & p_1 = p_2 \wedge a_1 \neq a_2 \wedge pr_1 \leq pr_2 \end{cases}$$

$$OT\left(\text{INS}(a_1, p_1, pr_1), \text{DEL}(_, p_2, pr_2) \right) = \begin{cases} \text{INS}(a_1, p_1, pr_1) & p_1 \leq p_2 \\ \text{INS}(a_1, p_1 - 1, pr_1) & p_1 > p_2 \end{cases}$$

$$OT\left(\text{DEL}(_, p_1, pr_1), \text{INS}(a_2, p_2, pr_2) \right) = \begin{cases} \text{DEL}(_, p_1, pr_1) & p_1 < p_2 \\ \text{DEL}(_, p_1 + 1, pr_1) & p_1 \geq p_2 \end{cases}$$

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定理 (RW-CLOSURE 算法正确性)

VPC-MU 实例满足 PRAM 一致性



RW-CLOSURE 算法所得图是 DAG 图

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证明

“ \implies ” 反证法

“ \impliedby ” 难点: DAG 图蕴含着多个全序

技巧: 对读操作作数学归纳, 构造合法调度

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RW-CLOSURE 算法复杂度:

$$\underbrace{O(n^2)}_{\# \text{loops}} \cdot \underbrace{O(n^3)}_{\text{transitive closure}} = O(n^5)$$

READ-CENTRIC 算法复杂度:

$$\underbrace{O(n)}_{\text{iterations}} \cdot \underbrace{O(n \cdot n^2)}_{\text{TOPO-SCHEDULE}} = O(n^4)$$

引理 (TOPO-SCHEDULE 的非迭代性)

设 TOPO-SCHEDULE 正在处理读操作 r ,
则局部子图中的每个写操作**最多只有一次机会**
在满足规则 $w'wr$ 的三元组中扮演 “ w' 角色”。

实验评估

实验目的¹：

1. 考察 READ-CENTRIC 算法的实际效率 (*vs.* 渐近时间复杂度)
2. 对比 READ-CENTRIC 算法与 RW-CLOSURE 算法的效率

¹机器配置: Intel Core i7 3.40GHZ, 4GB RAM.

实验评估

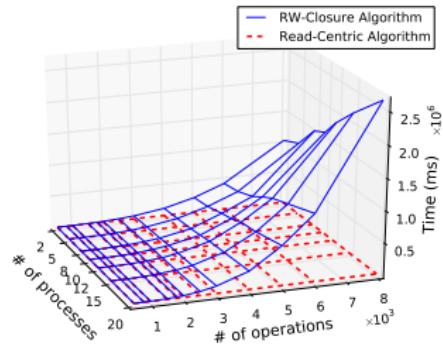
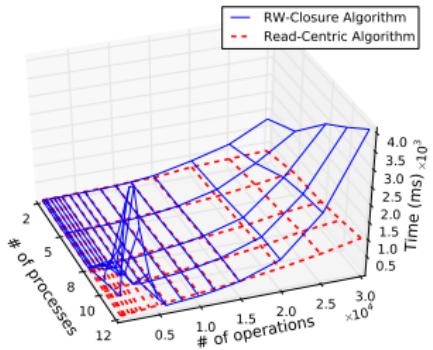
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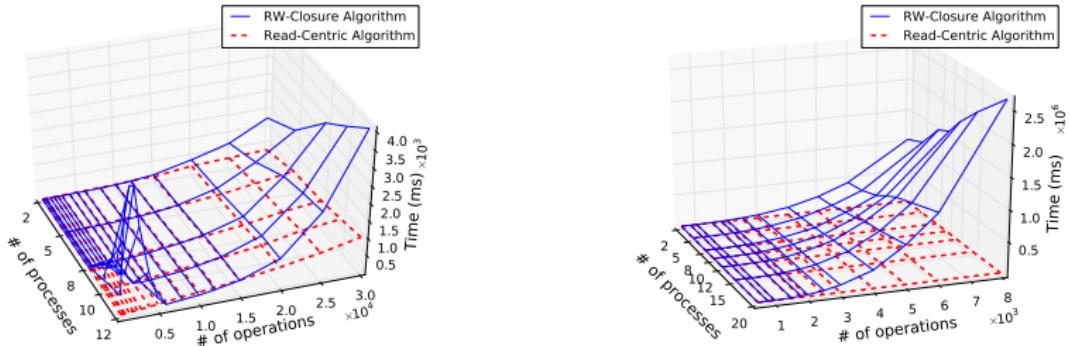
两类负载：

1. 随机生成的系统执行
2. 满足 PRAM 一致性的系统执行 (≈ 最坏情况输入)

¹机器配置: Intel Core i7 3.40GHZ, 4GB RAM.

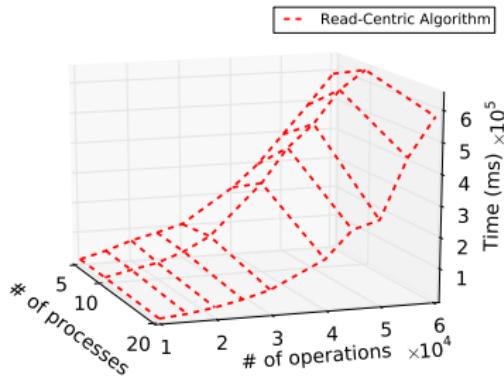


RW-CLOSURE 算法与 READ-CENTRIC 算法在 (左) 随机生成的执行及 (右) 满足 PRAM 一致性的执行上的运行时间。



RW-CLOSURE 算法与 READ-CENTRIC 算法在 (左) 随机生成的执行及 (右) 满足 PRAM 一致性的执行上的运行时间。

(右) 20 个进程、8,000 个操作:
READ-CENTRIC 可获得 694 倍加速.



READ-CENTRIC 算法在满足 PRAM 一致性的执行上的运行时间

READ-CENTRIC: 20 个进程、60,000 个操作 < 600s ¹

RW-CLOSURE: 20 个进程、8,000 个操作 > 3,000s

¹ 用于测试，规模可用

\mathcal{I} -Atomicity = i -实时序 + 读写语义

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$$f(\{\text{inversions}\}) \leq i$$

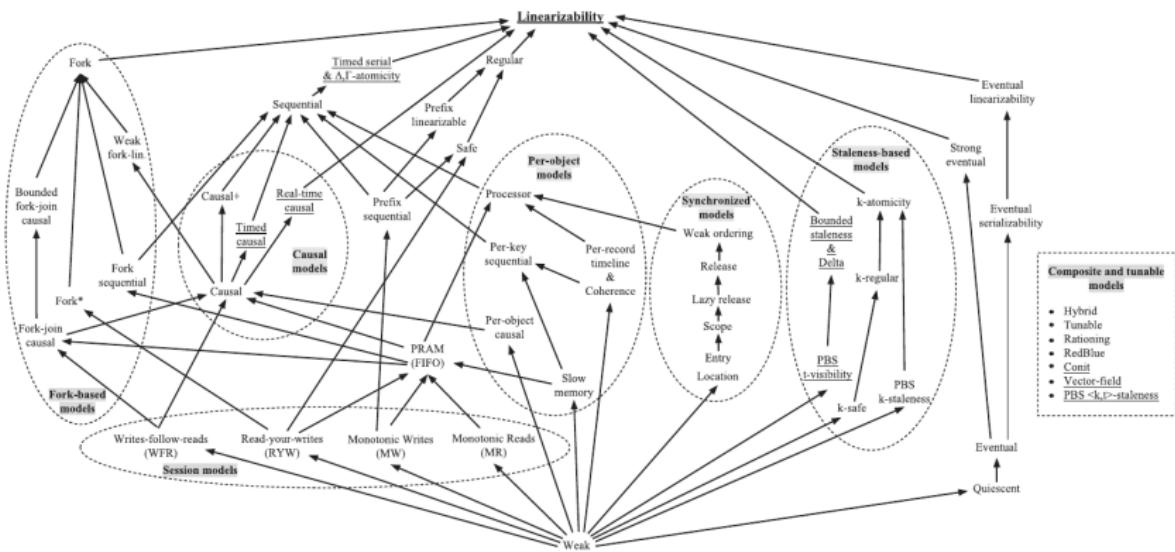
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\mathcal{I} : Inversions

$$f(\{\text{inversions}\}) \leq i$$

定义框架

(50 种) 一致性模型 关系图 [Viotti and Vukolić, 2016] [Burckhardt, 2014]



建立统一的形式化框架