无锁编程简介

An Intro to Lock-free Programming

吕慧伟

ASG 小组讨论班

http://asg.ict.ac.cn/lhw

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提纲

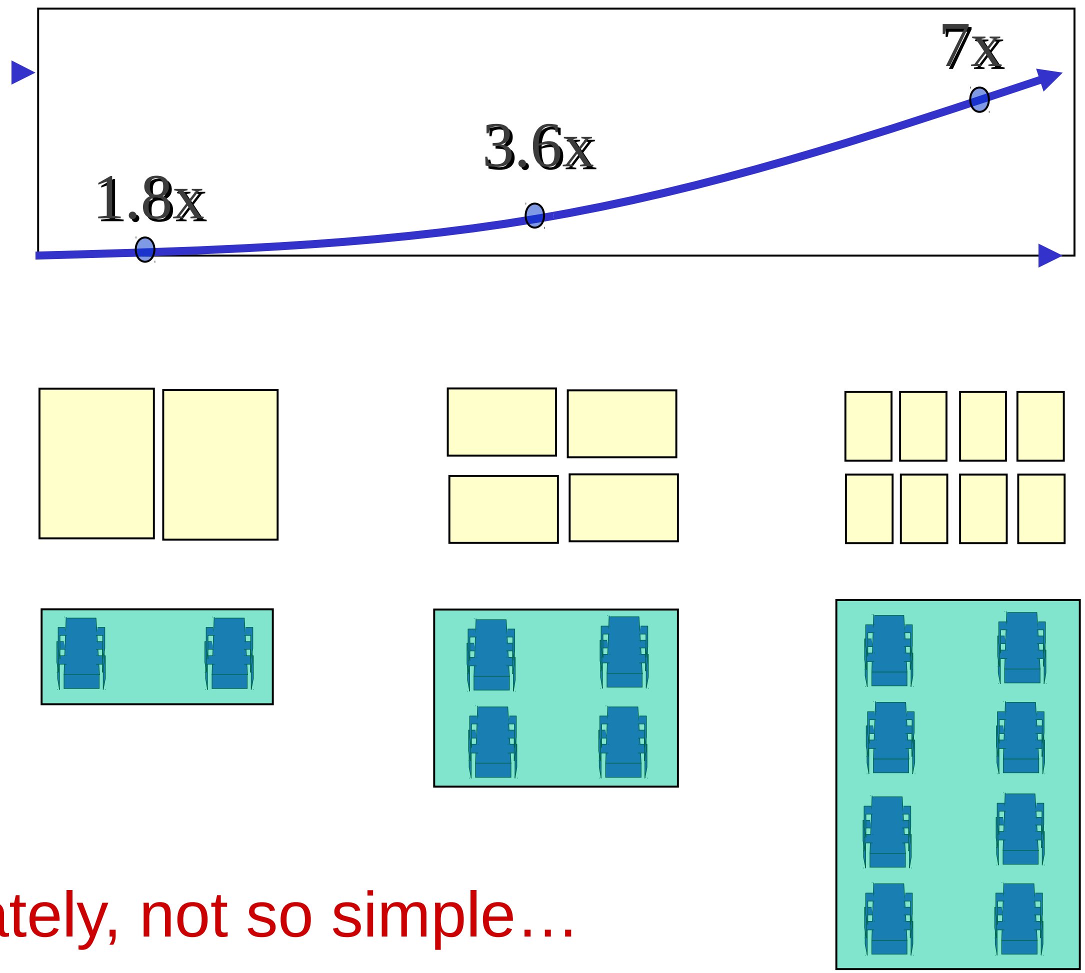
- 无锁编程概述
  - 动机：锁开销影响并行程序扩展性
  - What/Why/How
- 无锁编程实例
  - 无锁队列
- 无锁编程研究问题
  - 事务内存
  - 无锁数据结构

Multicore Scaling Process

Speedup

User code

Multicore



Unfortunately, not so simple…

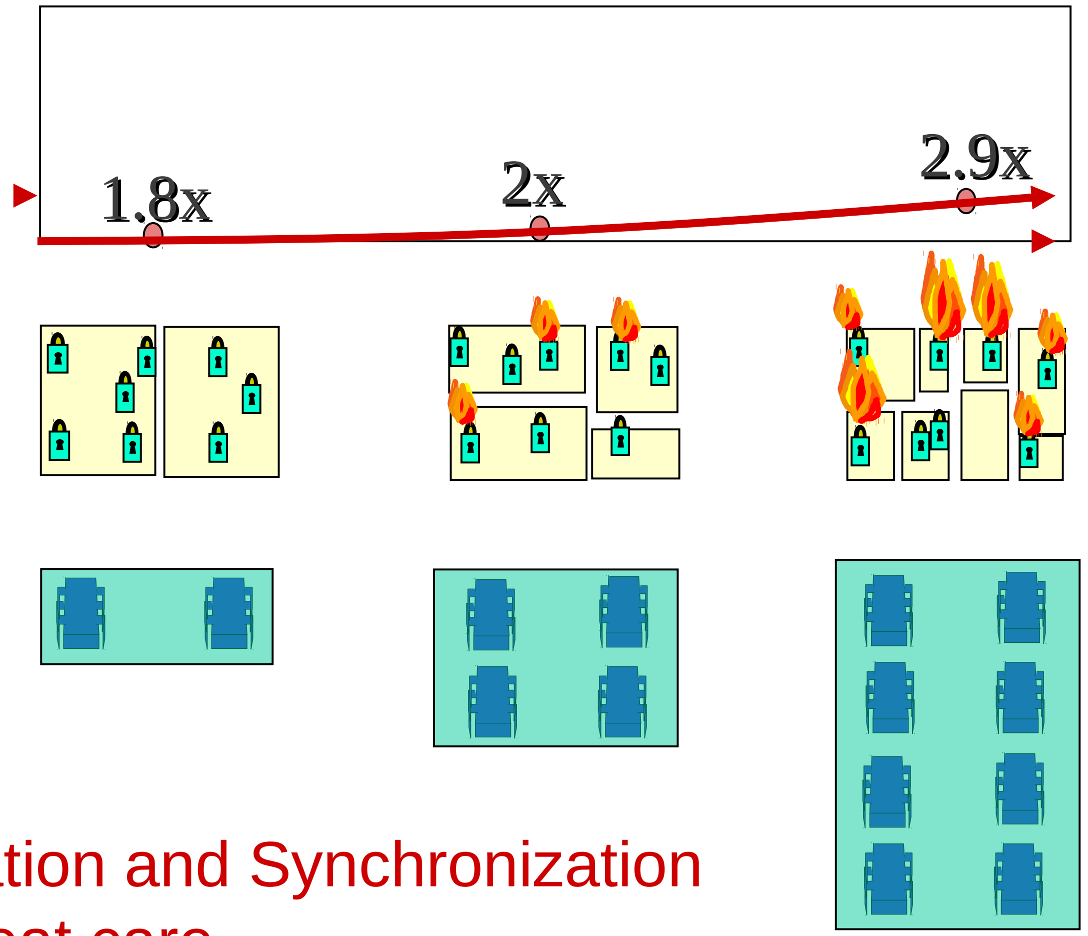
[Maurice 08]

Real-World Scaling Process

Speedup

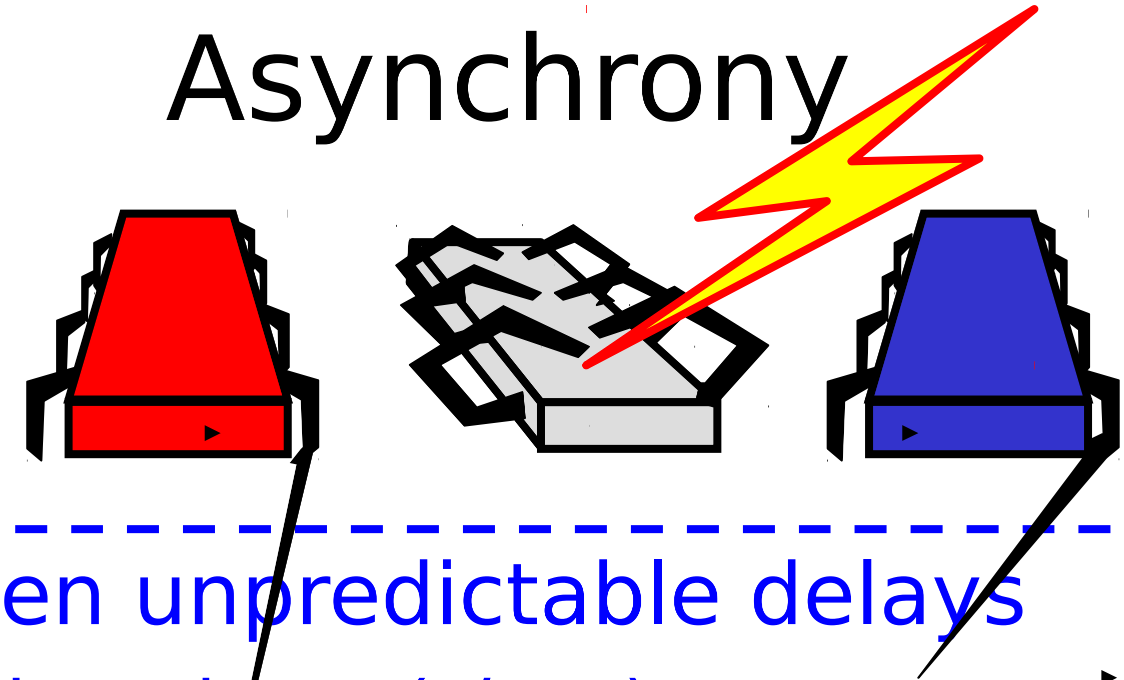
User code

Multicore



Parallelization and Synchronization require great care…

Asynchrony



- Sudden unpredictable delays
  - Cache misses (*short*)
  - Page faults (*long*)
  - Scheduling quantum used up (*really long*)

What: 什么是无锁编程？

- 如果一个共享数据结构的操作不需要互斥，那么它是无锁的。如果一个进程在操作中间被中断，其他进程的操作不受影响。[Herlihy 1991]
- 并行算法同步的分类
  - 阻塞同步(mutex,semaphore,...)
  - 无阻塞同步[LLF10]
    - 无等待∈无锁∈无阻碍
    - wait-free∈lock-free∈obstruction-free

Why: 为什么要无锁？

- 性能考虑
  - 对一些应用性能更好
- 避免锁的使用引起的错误和问题
  - 死锁：两个以上进程互等结束
  - Convoy：多个进程反复竞争同一个锁，抢占锁失败后强制上下文切换。引起性能下降。
  - 优先级反转：低优先级进程拥有锁时被抢占

How: 如何无锁？

- 方法：像事务一样操作 [DRD08]，知道谁拥有数据
  - 不同进程对私有数据更新互相隔离
  - 提交操作是原子的：或者成功，或者丢弃
  - 一致性：确保从一个状态变到另一状态
- 工具：原子指令
- 使用注意点
  - 无锁算法要求从硬件并行的角度考虑算法
  - 设计通用无锁算法很困难，一般只设计无锁的数据结构

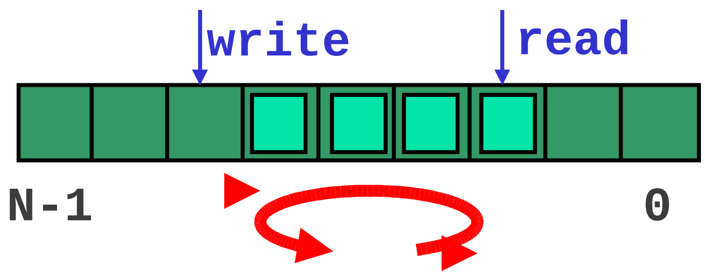
提纲

- 无锁编程概述
- 无锁编程实例
  - 单生产者单消费者FIFO：不需要原子指令
  - 多生产者多消费者FIFO：原子指令
  - 无锁堆栈、ABA问题
- 无锁编程研究问题

Lamport's Lock-Free Ring Buffer

[Lamport, Comm. of ACM, 1977]

- Operate on control variables: **read** and **write**, which resp. point to next read and write slots



NEXT(x) = (x + 1) % N

```
Insert(T element)
1: wait until NEXT(write) != read
2: buffer[write] = element
3: write = NEXT(write)
```

```
Extract(T* element)
1: wait until read != write
2: *element = buffer[read]
3: read = NEXT(read)
```

slide taken from [Lee10]

Compare-and-Swap

atomically

```
val CAS( val* addr, val old, val new)
{
    val prev = *addr;
    if (prev == old) { *addr = new; }
    return prev;
}
```

- *CMPXCHG (with "lock") – Intel x86*
- *Load Linked / Store Conditional – MIPS, PowerPC*

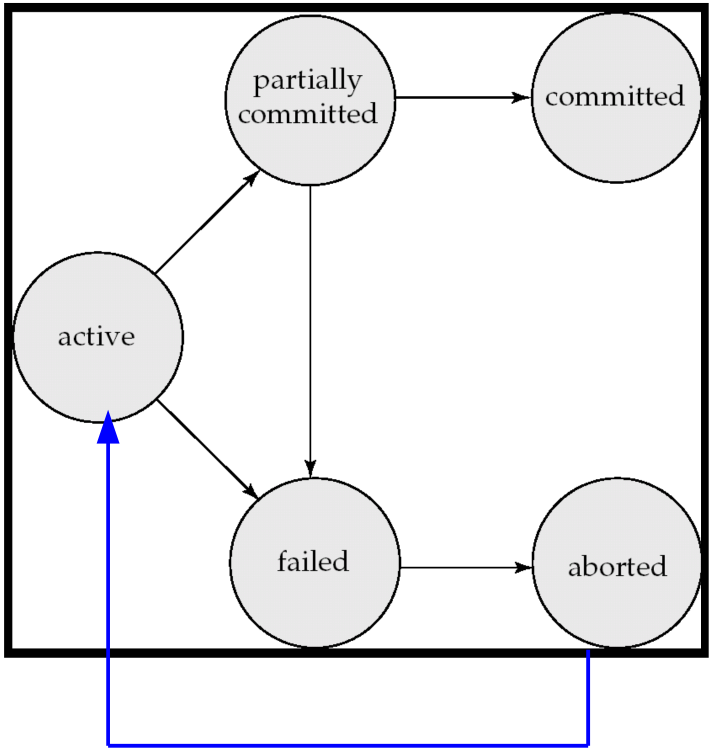
slide taken from [CS380D]

多生产者多消费者

FIFO

```
void enQ(request, queue)
{
    do{
        local_head = queue->head;
        request->next = queue->head;
        val = cmpxchg(&queue->head,
local_head, request);
    }while(val != local_head)
}
```

事务操作状态



Atomic & Consistency: cmpxchg
Isolation: 私有数据

多生产者多消费者

FIFO

```
void enQ(request, queue)
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    do{
        local_head = queue->head;
        request->next = queue->head;
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local_head, request);
    }while(val != local_head)
}
```
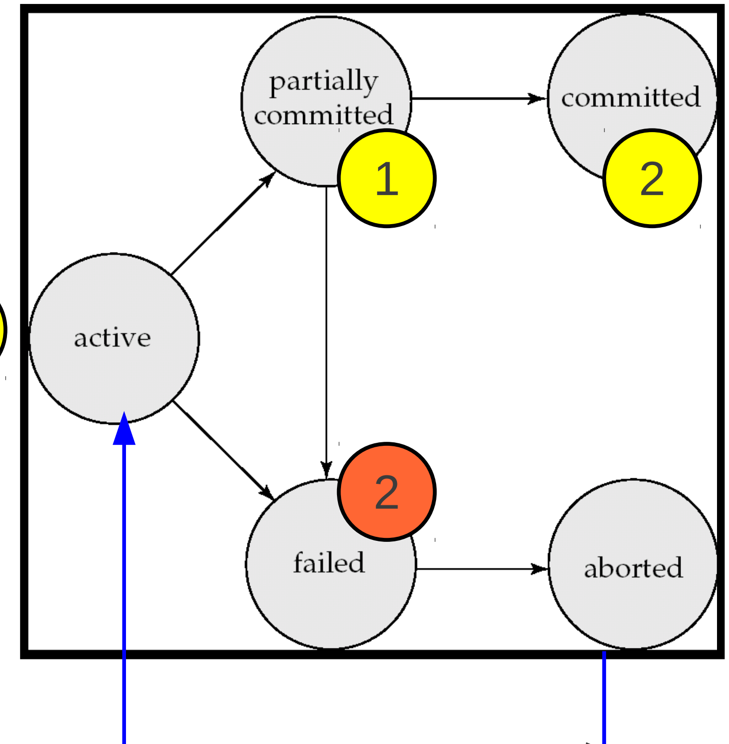

事务操作状态



如果在执行 cmpxchg 时 , queue->head == local_head 。即在 1, 2 之间没有进程将 queue->head 更改了。则 request 赋给了 queue->head 否则，上述过程将重新进行

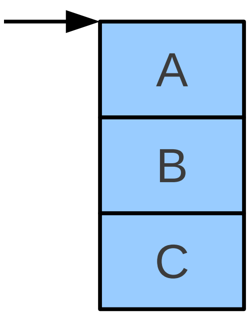
无锁堆栈

```
struct elem {
  elem *link
  any data;
}

elem *qhead;
```

```
Push (elem *x)
  do
    old = qhead;
    x->link = old;
    new = x;
    cc = CAS(qhead, old, new);
  until (cc == old;)
```

```
Pop ()
  do
    old = qhead;
    new = old->link;
    cc = CAS(qhead, old, new);
  until (cc == old;)
  return old;
```

ABA 问题



thread 1:

pop()

thread 2:

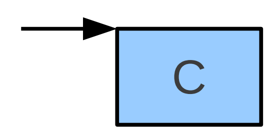
pop()

pop()

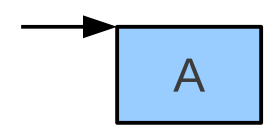
push(A)

正确执行：

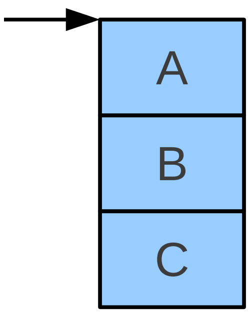
pop(); pop(); push(A); pop();



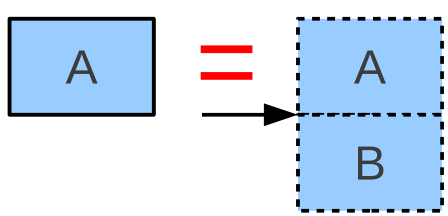
pop(); pop(); pop(); push(A);



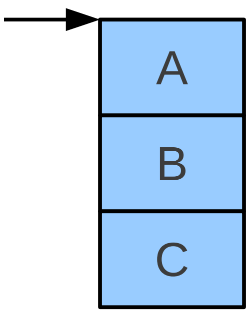
ABA 问题




```
pop()
  ret = A;
  next = B;
  // interrupted
  CAS(A,A,B)
```



ABA 问题

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pop()
  ret = A;
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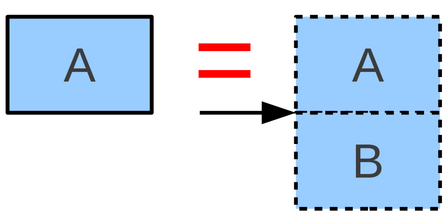
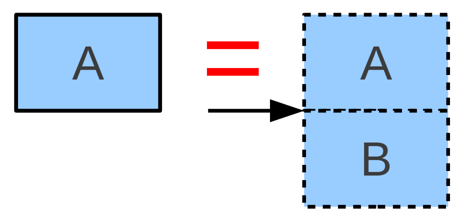
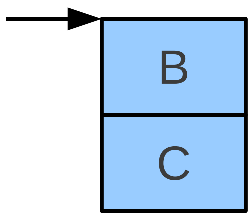



```
pop()
  ret = A;
  next = B;
  CAS(A,A,B)
```



ABA 问题




```
// interrupted       pop()
  CAS(A,A,B)            ret = B;
                        next = C;
                        CAS(B,B,C)
                        return B;
```

ABA 问题

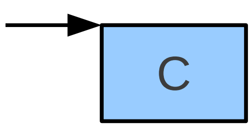
// interrupted

CAS(A,A,B)

push(A)

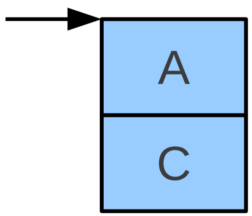
A->next = C;

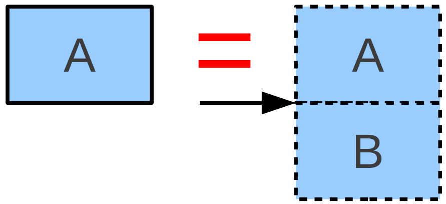
CAS(C,C,A)



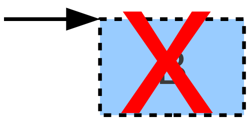
ABA 问题

// resumes
CAS(A,A,B)





ABA 问题



// resumes

CAS(A,A,B)

Stack with DWCAS

```
struct elem {          struct qhead {
  elem *link;            elem *link;
  any data;              int seq;      <-- version number
}                      } qhead;
```

```
Push(elem *x)
  do
    old = qhead.link;
    oldseq = qhead.seq;
    x->link = old;
    cc = DWCAS(qhead,
               <old, oldseq>,
               <x, oldseq+1>);
  until (cc);
```

```
Pop()
  do
    old = qhead.link;
    oldseq = qhead.seq;
    new = old->link;
    cc = DWCAS(qhead,
               <old, oldseq>,
               <new, oldseq+1>);
  until (cc);
  return old;
```

slide taken from [CS380D]

提纲

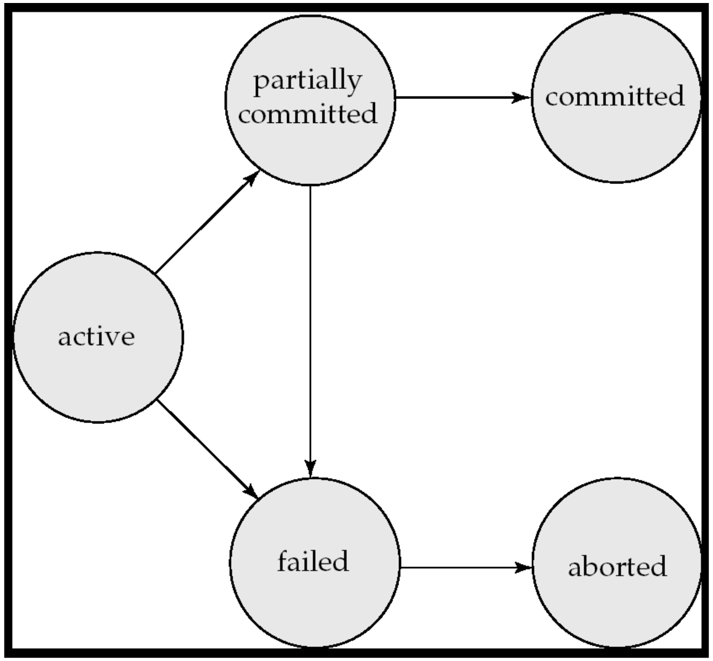
- 无锁编程概述
- 无锁编程实例
- 无锁编程研究问题
  - 无锁数据结构
  - Transactional Memory

事务内存

Transactional Memory

为什么叫 Transactional Memory

- 从 Database 的核心概念 Transaction 借鉴
- Database 一次 Transaction 过程
  - 1. Begin the transaction
  - 2. Execute several data manipulations and queries
  - 3. If no errors occur then commit the transaction and end it
  - 4. If errors occur then rollback the transaction and end it
- ACI 特征 (Atomicity, Consistency, Isolation)



Transaction State

Transactional Memory [TM M.K.]

- 1977 Lomet
  - (发现一种) 保证共享数据的抽象机制
- 1993 Herlihy and Moss, ISCA
  - Transactional Memory - architectural support for lock-free data structures
  - 支持无锁数据结构的机制
- ISCA, HPCA, PPoPP, PODC…
  - Challenge: to build an efficient TM infrastructure

Herlihy and Moss, ISCA 1993

[TM M.K.]

- coined the term *Transactional Memory*
- 增加 6 种新指令供程序员构建无锁数据结构
  - *load-transactional*: 读数据到私有寄存器
  - *load-transactional-exclusive*: 读数据到私有寄存器，如果 cache-miss，请求数据所有权
  - *store-transactional*：写到内存 (cache) 但其他进程在 commit 之前不可见
  - *commit*: 提交内存更改
  - *abort*: 丢弃写更改
  - *validate*: 查询当前事务状态

Herlihy and Moss, ISCA 1993

[TM M.K.]

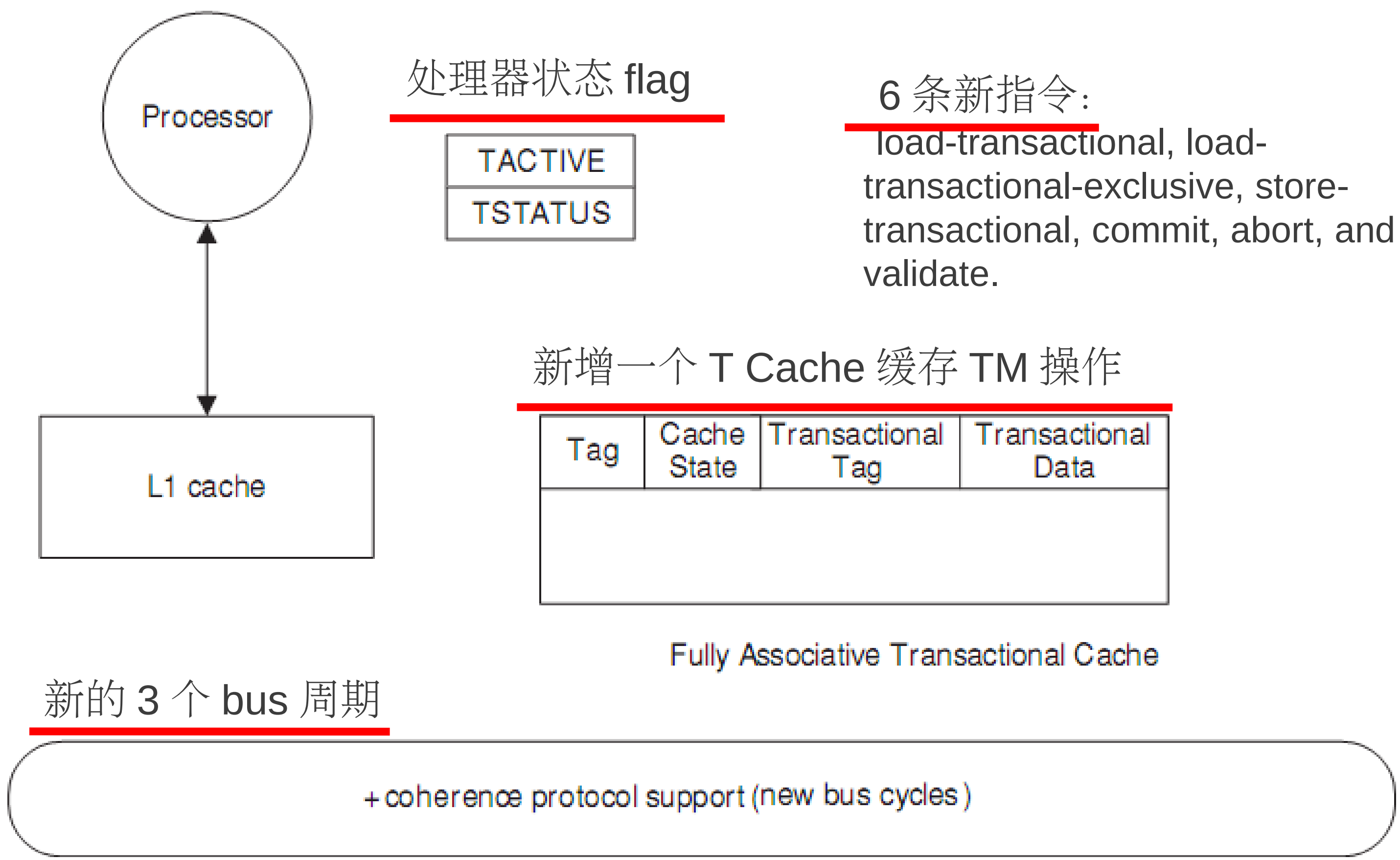


FIGURE 4.7: Herlihy and Moss Ttransactional Mmemory support

Transactional Memory [TM M.K.]

- TM 如何解决线程级并行?
  - 程序员把计算 wrap 成 transaction
  - 不是万能药，但是把同步操作从程序员转移到编译器、运行环境和硬件
  - 目前主要的信心来自 transaction 解决了数据库的问题。尚没有用 TM 来解决一般的并行编程问题。
  - 目前还只是语义级别的 TM 定义 (尚没有编译器、运行环境、库的支持)
  - TM 会和非 TM 的代码并存很长一段时间。 TM 的成功取决于旧代码和新代码的无缝结合。

小结

- 无锁编程可以避免使用锁的一些常见错误，并有可能带来性能提高
- 设计通用的无锁算法很难，目前常见的有一些无锁的数据结构
- 无锁的数据结构要求按照事务处理的方式编程
- 事务内存是对无锁的支持，目前研究很热，难点在于有效的实现

参考资料

- [DRD08]Dr Dobbs, Writing Lock-Free Code: A Corrected Queue, http://drdobbs.com/high-performance-computing/210604448
- [LLF10] 杨小华，透过 Linux 内核看无锁编程 ,http://www.ibm.com/developerworks/cn/linux/l-cn-lockfree/
- [Maurice 08]Maurice Herlichy and Nir Shavit, The Art of Multiprocessor Programming
- [TM M.K.] James R. Larus and Ravi Rajwar, Transactional Memory, published by Morgan Kaufman

参考资料

- [Herlihy 1991]Maurice Herlihy, Wait-free Synchronization,1991
- [NSYNC]Nonblocking synchronization bibliography, http://www.cs.wisc.edu/trans-memory/biblio/swnbs.html
- [Langdale05]Geoff Langdale, Lock-Free Programming, www.cs.cmu.edu/~410-s05/lectures/L31_LockFree.pdf
- [Lee10]Patrick P.C. Lee, A Lock-Free, Cache-Efficient Multi-Core Synchronization Mechanism for Line-Rate Network Traffic Monitoring

参考资料

- [CS380D]Wait-Free Synchronization Lecture, CS380D—Distributed Computing, The University of Texas at Austin