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Distributed Computing Group

Multi-Core Computing with Transactional Memory

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Overview

- Introduction
- Difficulties with parallel (multi-core) programming
- A (partial) solution: Transactional Memory
- Contention Management

Multi-cores will be everywhere

- To increase computing speed, traditionally the clock speed of a CPU was increased
  - Problem: Overheating
- New approach: Have many cores on a single die
- Multi-core chips are used in every PC and soon in every mobile phone
- It is likely that we see a doubling of cores every 2 years like we saw a doubling of clock speed
- BUT: Parallel programming brings new problems and adds complexity for software engineers

Why is parallel programming more difficult?

- We need synchronization…
  - Parallel reservation system for cinema tickets without synchronization

Time	Thread 1 - Return 5 tickets	n = Number of sold tickets	Thread 2 - Buy 3 tickets
0		100	
1	Read n (Return 100)	100	
2		100	Read n (Return 100)
3	New value for n: 100-5 =95 Set n to 95	95	
4		103	New value for n: 100+3=103 Set n to 103

Two kinds of parallelism

- Data parallelism
  - different data for each thread (running on a core)
  - every core works separately
  - No overlapping, no problem!
  - Ex.: Each thread sorts a given set of data unknown to other threads
- Task parallelism
  - several tasks working on same/overlapping data
  - Ex.: All threads insert/delete elements in the same tree

Concurrent programming today

- Synchronization using locks or monitors
  - Locks implemented via test-and-set or compare and swap operations
  - Monitor : Mutual exclusion
    - e.g. java “synchronized method”
    - Easy but slow -> only 1 thread runs at a time
- Coarse grained vs. fine grained locking

Coarse grained	fine grained locking
easy but slow program	difficult, cumbersome but fast programs
Little(no) parallelism	lots of code, deadlocks…

```
lock all data
modify/use data
unlock all data
```

Only 1 thread can operate on the data

```
lock Element A
lock Element B
modify/use A,B
lock Element C
modify/use A,B,C
unlock A
modify/use B,C
unlock B,C
```

```
lock Element B
lock Element A
modify/use A,B
unlock A,B
```

Deadlock possible: Thread 1 locks A, while Thread 2 locks B, then both are stuck…

Example: Deleting an element from a linked list

- Sequential code/Coarse grained locking
  - < 10 lines of code
- Concurrent linked list: See below…

The List::delete method attempts to remove a node containing the supplied key.

```
public boolean List::delete (KeyType search_key) {
  Node *right_node, *right_node_next, *left_node;

  do {
    right_node = search (search_key, &left_node);
    if ((right_node == tail) || (right_node.key != search_key)) /*T1*/
      return false;
    right_node_next = right_node.next;
    if (!is_marked_reference(right_node_next))
      if (CAS (&(right_node.next), /*C3*/
          right_node_next, get_marked_reference (right_node_next)))
        break;
  } while (true); /*B4*/
  if (!CAS (&(left_node.next), right_node, right_node_next)) /*C4*/
    right_node = search (right_node.key, &left_node);
  return true;
}
```

```
private Node *List::search (KeyType search_key, Node **left_node) {
  Node *left_node_next, *right_node;

search_again:
  do {
    Node *t = head;
    Node *t_next = head.next;

    /* 1: Find left_node and right_node */
    do {
      if (!is_marked_reference(t_next)) {
        (*left_node) = t;
        left_node_next = t_next;
      }
      t = get_unmarked_reference(t_next);
      if (t == tail) break;
      t_next = t.next;
    } while (is_marked_reference(t_next) || (t.key<search_key)); /*B1*/
    right_node = t;

    /* 2: Check nodes are adjacent */
    if (left_node_next == right_node)
      if ((right_node != tail) && is_marked_reference(right_node.next))
        goto search_again; /*G1*/
      else
        return right_node; /*R1*/

    /* 3: Remove one or more marked nodes */
    if (CAS (&(left_node.next), left_node_next, right_node)) /*C1*/
      if ((right_node != tail) && is_marked_reference(right_node.next))
        goto search_again; /*G2*/
      else
        return right_node; /*R2*/
  } while (true); /*B2*/
```

More problems with locking - Composability

- How to compose objects/components using locks
- If locks are external then programmer must handle locking himself
  - cumbersome(lots of code), error-prone (deadlocks)
- If locks are internal then it is not possible to achieve all desired behaviors
  - Example: Hash table T1 (contains number 1) and T2 (empty)
    No duplicates, each element unique
    2 threads moving elements between tables

```
Algorithm Move(Element e, Table from, Table to)
if from.find(e) then
    to.insert(e)
    from.delete(e)
end if
```

Example continued…

- Threads might be delayed for some reasons: interrupts, cache miss…

	Table T1 contains 1 and T2 is empty	
Time	Thread 1	Thread 2
	Move(1,T1,T2)	Move(1,T2,T1)
1	T1.find(1)	delayed
2	T2.insert(1)	
3	delayed	T2.find(1)
4		T1.insert(1)
5	T1.delete(1)	T2.delete(1)
	both T1 and T2 are empty	

- Where is the '1'?

Transactional memory(TM) - a (partial) solution

- Simple for the programmer

```
Begin transaction
modify/use data
End transaction
```

- Composable

```
Algorithm Move(Element e, Table from, Table to)
Begin Transaction
if from.find(e) then
    …
End Transaction
```

```
Method Table.find(Element e)
Begin transaction
   …
End transaction
```

- Many TM systems (internally) still use locks
- But the TM system (not the programmer) cares about
  - Performance
  - Progress/correctness (no deadlocks...)

What is a transaction?

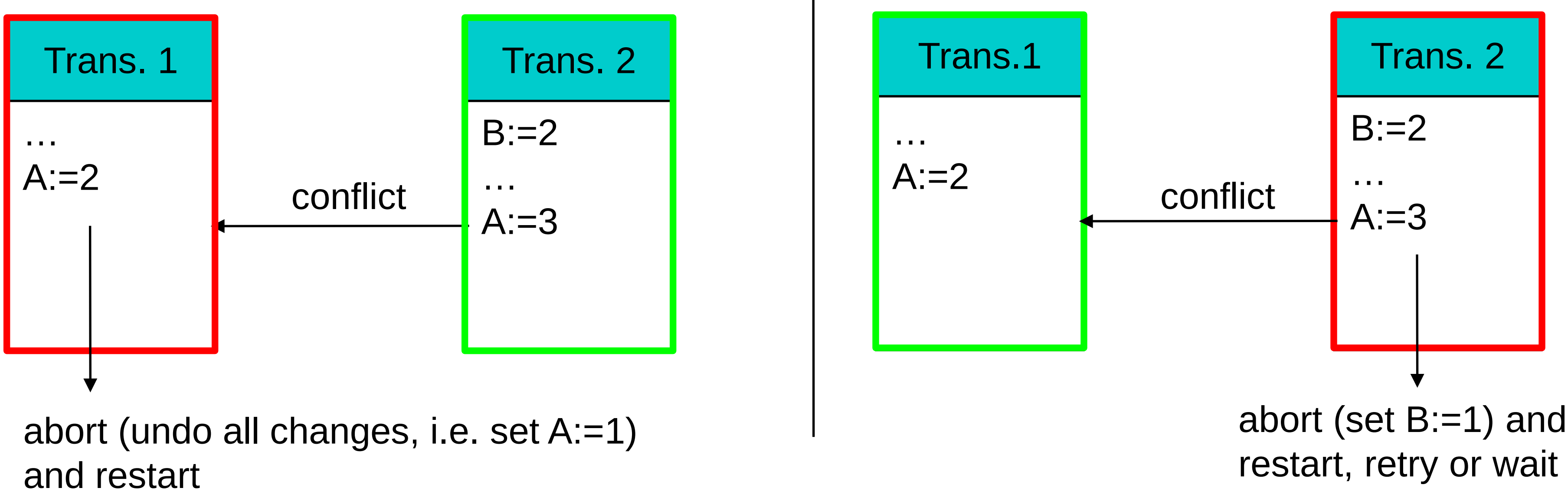
- Nothing new, has been used in databases for a long time
- Characterized by 3 properties (ACI)
  - Atomicity
    - Either a transaction finishes all its operations or no operation has an effect on the system
  - Consistency
    - All objects are in a valid state before and after the transaction
  - Isolation
    - A transaction cannot access or see data in an intermediate (possibly invalid) state of any parallel running transactions.
- For databases also durability
  - If a transaction has completed, its changes are permanent
    - Written on a disk not just in memory

Implementation of a TM system

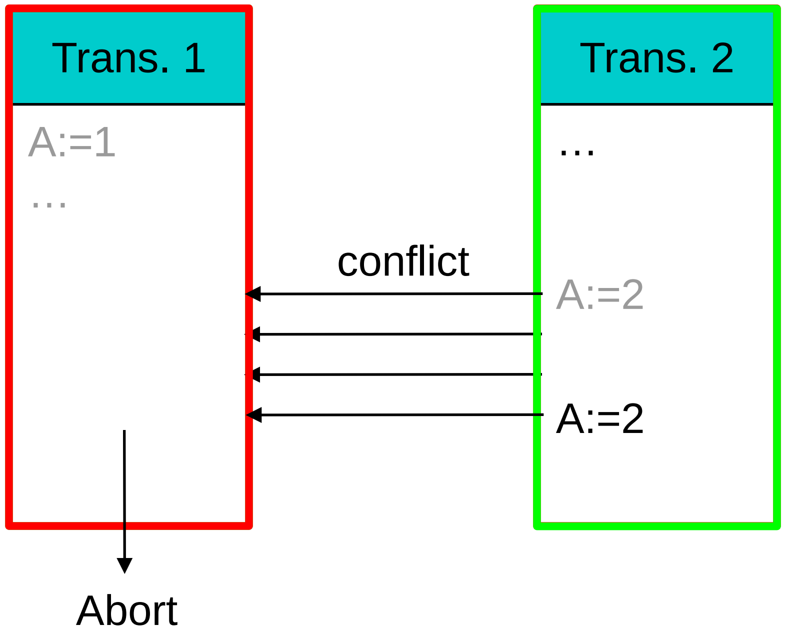
- Systems exist in hardware, software and as a mix (hybrid)
- (Usually) transactions are executed optimistically
  - i.e. without knowing whether they use the same data
- If transactions work on
  - different data, everything is ok
  - modify the same data, conflicts arise that must be resolved…
    - Transactions might get delayed (has to wait) or aborted.
- A transaction keeps track of all modified values and restores all values, if it is aborted due to a conflict.
- A transaction successfully finishes with a commit
  - Only after the commit, other transactions notice its changes.

Conflicts – A contention manager decides

- A contention manager can abort or delay a transaction
- Important impact on performance
- Example
  - Initially: A=1, B=1



Just another example of a contention manager



Why is TM only a partial solution? – Open issues

- I/O support
  - Imagine a document is printed within a transaction and the transaction gets aborted => waste of paper
- Interaction with old, non-transactional (legacy) code
- Efficiency
  - TM still too slow, but catching up quickly…

- Despite the problems:
  - TM system already on the market, partially supporting hardware TM
  - many software TM libraries exist

Open issues from a research perspective

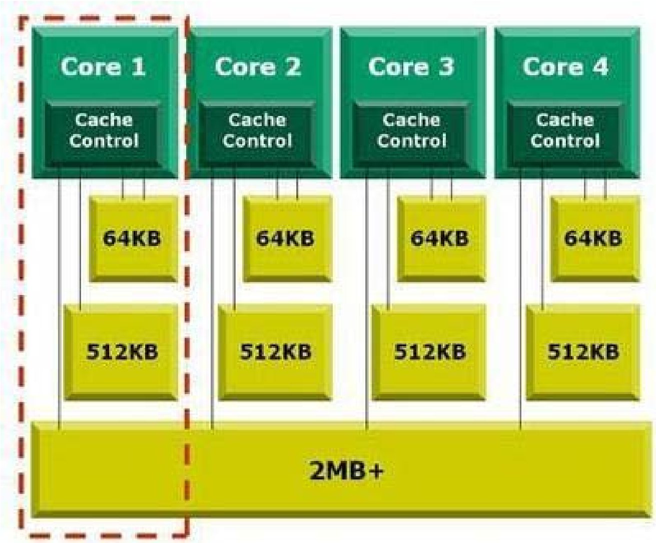
- Why research?
  - Help understanding to improve efficiency
  - create (provable) secure systems

- System model not sufficient
  - PRAM: assumes threads are synchronous

    only read/write access to memory

    (e.g. no test and set)

    no multilevel caching



- How to resolve conflicts?
  - What is the ‘best’ contention manager?

Some theory on contention management

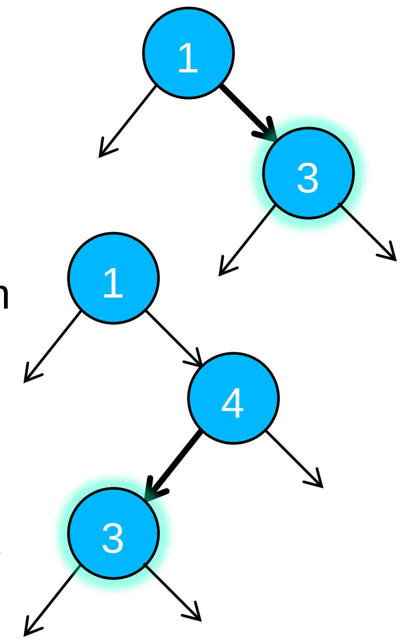
- Model: *n* transactions (and threads) starting concurrently on *n* cores
- *S* (shared) resources (variables/objects)
- Transaction = sequence of operations
- Operation:
  - takes 1 time unit
  - 2 kinds: Write, compute/abort/commit
  - Write = modify (shared) resource and lock it until commit
- A conflict arises if transaction A wants to lock a resource that is already locked by B

Model continued…

- A transaction demands unknown resources
  - Dynamic data structures change over time
  - Eg.:Binary tree, a transaction wants to insert 3

Initially: Must lock/modify right pointer of node 1

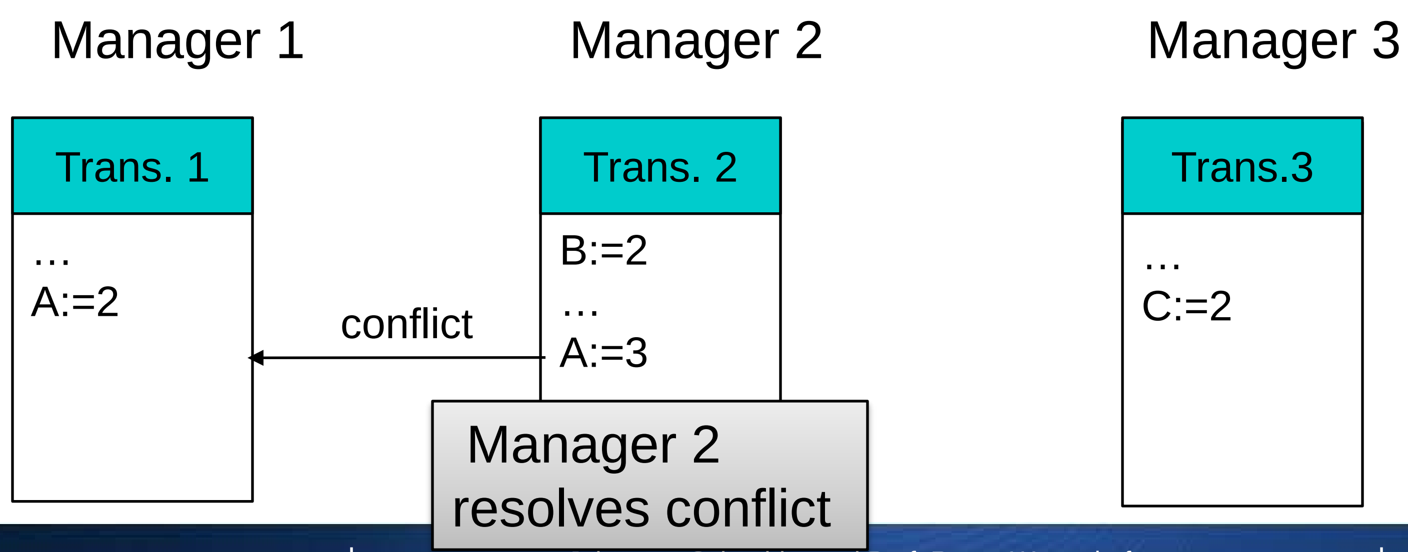
Assume transaction got aborted and another transaction inserted 4 meanwhile.
Now: Must lock/modify left pointer of node 4



- Duration(number of operations) is fixed
  - Not true, but mostly only a constant factor away
- Model is a simplification
  - Ex.: There are also reads
  - Ex.: a write access, does not always require a resource to be locked

Contention manager (CM)

- Distributed
  - Each thread has its own manager
- Does not know future(potential) conflicts
  - Conflicts also not learnable, might change
  - Online scheduling problem

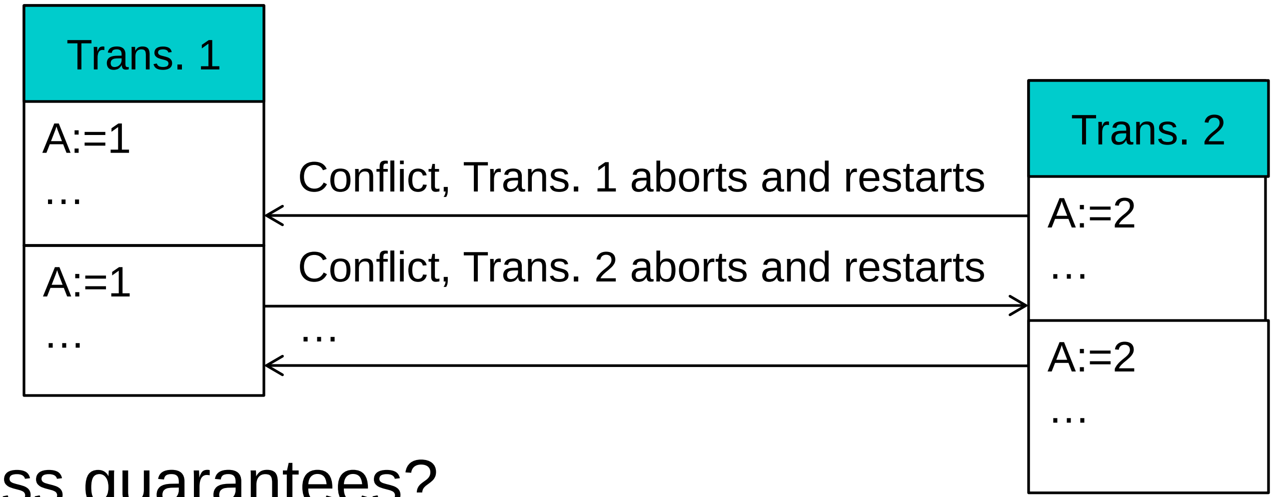


Properties of a contention manager

- Throughput
  - Makespan = How long it takes until all n transactions committed = length of a schedule
  - Schedule of transactions defined by decisions of CM
  - Look at worst case
  - Competitive ratio = makespan my CM / makespan optimal CM
    - Oblivious adversary = knows my CM (not random choices)
    - Optimal CM knows decisions of adversary and all conflicts…
- Progress guarantees
  - wait freedom (strongest guarantee)
    - all threads(transactions) make progress in a finite number of steps
  - lock freedom
    - one thread makes progress in a finite number of steps
  - obstruction freedom (weakest)
    - a thread makes progress in a finite number of steps in absence of contention (no conflicts, no shared data)

Example of a CM

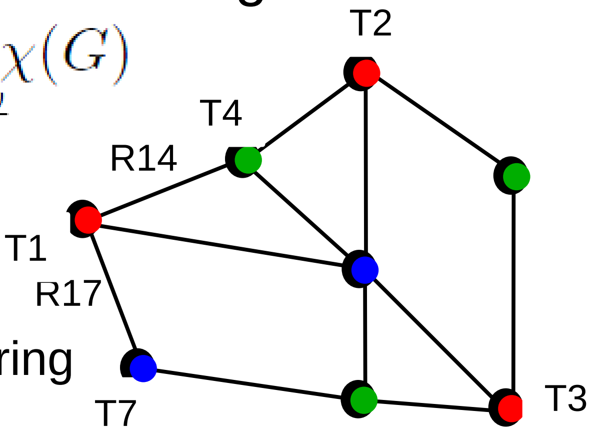
- Strategy: Be aggressive
  - If a transaction A wants a resource locked by B, then B is aborted
- Throughput?
  - (Possibly) none
    - Livelock: Transactions repeatedly abort each other
    - Eg: 2 Transactions that write/lock the same resource



- Progress guarantees?
  - Obstruction freedom

Problem complexity, it is (NP) hard…

- How long does it take to compute a good schedule?
  - = Is it NP-hard to approximate the optimal makespan by a constant factor?
- …as long as approximating an optimal vertex coloring
  - Optimal = Minimum number of colors = $\chi(G)$
  - NP-hard to compute a coloring with $\chi(G)^{\frac{\log \chi(G)}{25}}$



- Reduction to coloring
  - Graph -> Scheduling problem -> Schedule -> Coloring
  - Nodes = transactions
  - Edges = resources (conflicts)
  - Transactions have same duration ***t*** (=1)
  - Transactions of same color don't conflict

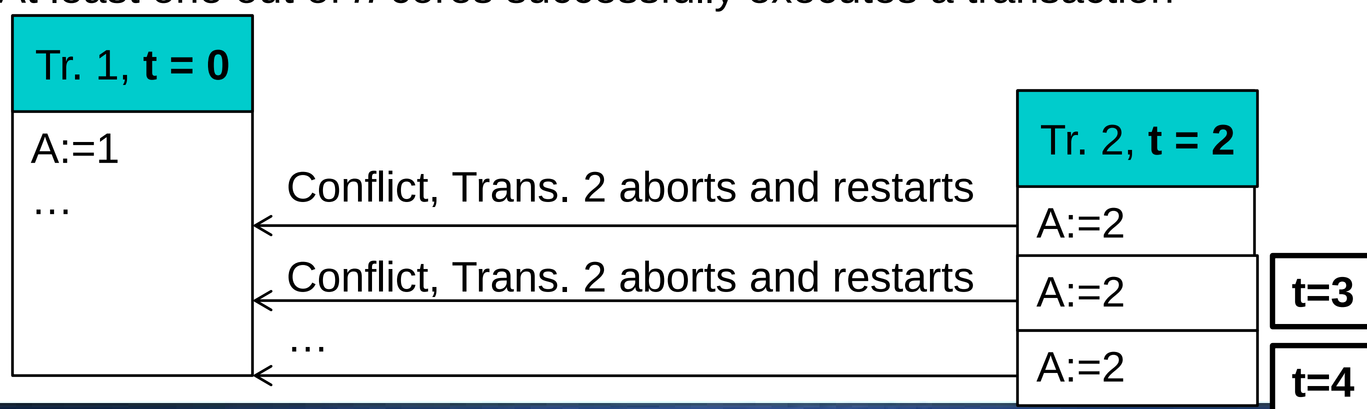
Time	**[0,t]**	**[t,2t]**	**[2t,3t]**
Trans. Run&commit	T1,T2,T3	T4,T5,T6	T7,T8

if resource acquisition takes almost no time, otherwise more complex

- This holds even, if all transactions (potential) conflicts are known and transactions don't change

It is hard, so what can be done? Another example…

- CM Strategy: Avoid wasting work
  - Approximate the work done
  - Each transaction gets a (unique) timestamp ***t*** on startup (and after an abort)
  - Conflict: The younger transaction, having performed less work, is aborted
- Throughput? Progress guarantees?
  - Oldest transaction will always commit
  - Lock freedom
    - At least one out of *n* cores successfully executes a transaction

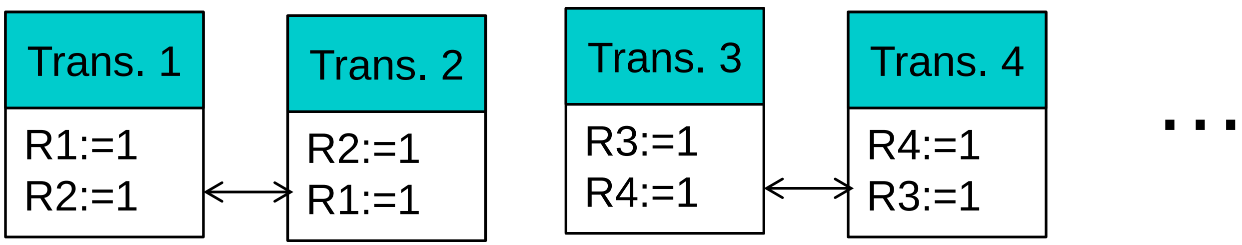


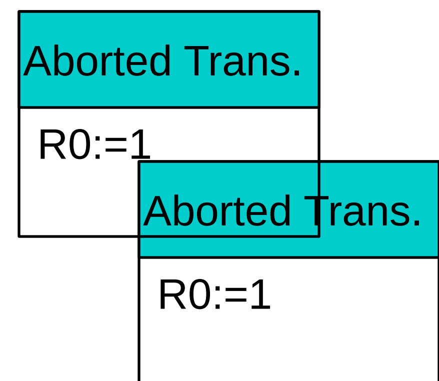
Competitive ratio of the time stamp manager

- *S* resources
- *n* transactions that start concurrently
- Assume each transaction T_i locks a resource directly after its start for its whole duration t_{Ti}
- Observe: At most *S* transactions can run in parallel
  - If *S+1* run in parallel at least 2 must attempt to lock the same resource
- Thus the optimal makespan is at least: $\sum_{i=0}^{n} \frac{t_{T_i}}{s}$.
- Makespan CM timestamp is at most: $\sum_{i=0}^{n} t_{T_i}$
  - all run sequentially in the worst case
- Competitive ratio = timestamp/ optimal $\frac{\sum_{i=0}^{n} t_{T_i}}{\sum_{i=0}^{n} \frac{t_{T_i}}{s}} = s = \Omega(s)$

Lower bound on competitive ratio

- Thm: Competitive ratio of any CM (deterministic and randomized) is $\Omega(n)$ if number of resources $S >= n$
- Proof (only for deterministic CM)



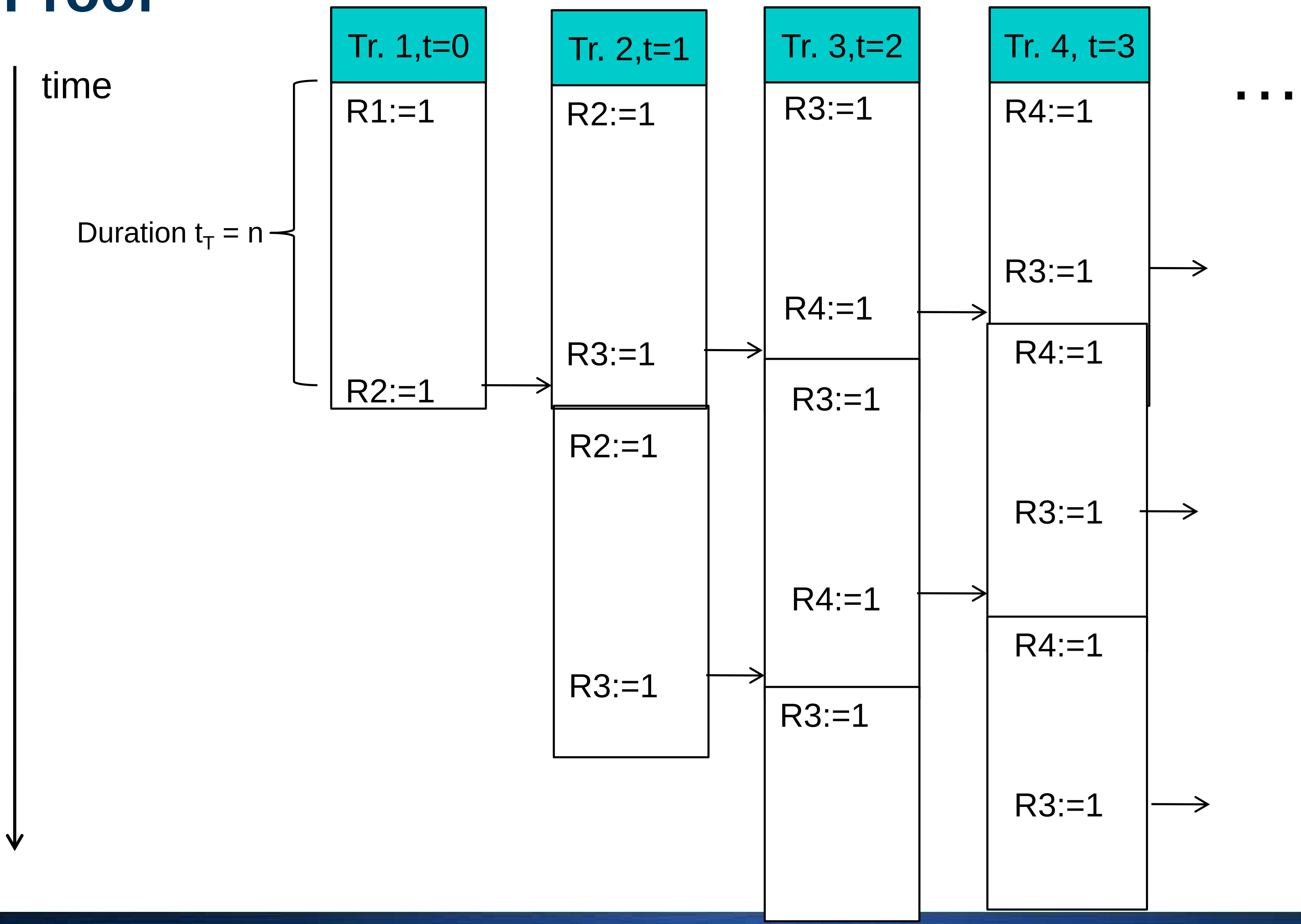


  - Any CM must abort ½ of all transactions S_T, say S_A
  - Adversary knows the aborted trans. S_A
  - She/he lets all of them lock the same resource R0
  - All aborted transaction (½ n) must run sequentially
  - Optimal lets all transactions S_A commit and aborts the other ½

Analysis of algorithm timestamp revisited

- For the lower bound the adversary reduced the parallelism dramatically
  - This is unlikely to happen
- Assume the demanded resources don't change over time
  - i.e. the adversary cannot reduce parallelism at run-time
- Is the competitive ratio still $\Omega(n)$ (for $S>=n$)?
  - Yes (proof next slide)
  - All transactions start concurrently
  - Adversary knows timestamps of all transactions

Proof

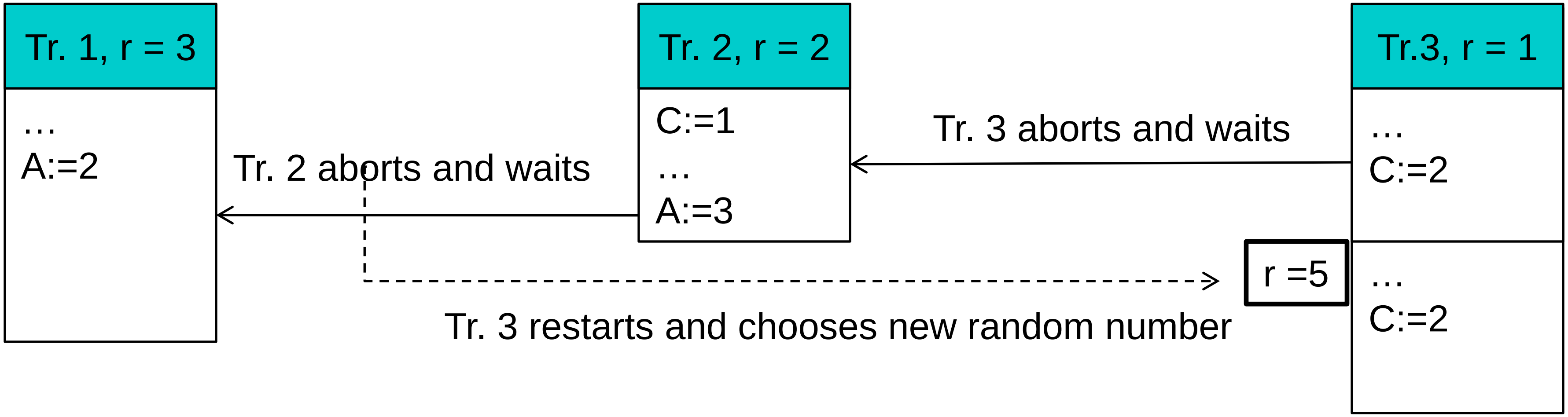

time
Duration t_T = n
Tr. 1,t=0
R1:=1
R2:=1
Tr. 2,t=1
R2:=1
R3:=1
R2:=1
R3:=1
Tr. 3,t=2
R3:=1
R4:=1
R3:=1
R4:=1
R3:=1
Tr. 4, t=3
R4:=1
R3:=1
R4:=1
R3:=1
R4:=1
R3:=1
...

Proof continued...

- Transaction Ti (>1) aborts at time n-i+1, Trans. 1 commits
- After a restart Transaction Ti (>2) aborts after running for time n-i+2, Trans. 2 commits
- After the next restart Transaction Ti (>3) aborts after running for time n-i+3, Trans. 3 commits
- The time until transaction i=n commits is $\sum_{i=1}^{n}(n-i) = \Omega(n^2)$
- Optimal:
  - Schedules all transaction Ti with even i then the rest
  - O(n)
- Competitive ratio: Ω(n)

How about a randomized approach?

- Choose a random priority ***r*** from [1,n] on startup
- Transaction A with larger or same random number wins conflict against B
  - B aborts and waits
  - Restart with a new random number as soon as A either commits or aborts



Analysis

- Assume:
  - (needed) resources are not modified
  - Longest transaction takes time ***t***
  - Any transaction conflicts with at most ***d*** other transactions
- After time 2 *t* any transaction can restart and draw a new random number
  - Execute for time *t*-1 and then aborts and wait for at most time *t*
- Probability highest rand. number: 1/*d*
- Prob. random number unique: $(1-1/n)^d < (1-1/n)^n \approx 1/e$
- Choose *d e* log *n* random numbers

  and probability to commit is: $1-(1-\frac{1}{e\cdot d})^{e\cdot d \cdot \log n} \approx 1-\frac{1}{e}^{\log n} = 1-\frac{1}{n}$

Analysis continued and evaluation

- Time to choose *d e log n* random numbers is *O(t d log n*)

- How good is the algorithm?
  - For the analysis of algorithm timestamp $d = 2$, $t = n$
    - Makespan of randomized CM: O(*n log n*) with 'high' probability
    - Deterministic timestamp: O(n^2)
  - Complexity measure
    - Originally: Dependent on number of resources
    - Now: Dependent on number of conflicts a transaction faces
    - Better?

Theory and practice

- For most benchmarks our randomized approach and a timestamp manager achieve comparable throughput
- In general, the quality of a CM varies very much across different benchmarks
  - A CM might be good for one benchmark but bad for another
- A strategy that is (often) good:
  - After a conflict do some kind of exponential randomized backoff
  - Reduces load on system, resolves livelocks

Exponential backoff

- Example: Polka manager
  - Approximate work: priority = number of accessed resources
  - In case of a conflict: If have higher priority abort the other, if have lower priority, then perform an exponential backoff
  - Say priority difference of the two transactions is ***r***

  - Algorithm:

For ***i*** = 0..***r***

If resource not locked then lock it

else wait random time span with mean $\mathbf{2}^{i}$

After ***r*** unsuccessful trials abort transaction with higher priority

Semester/master theses

- Check the homepage
  - www.dcg.ethz.ch/theses.html
- For TM: Currently, more practical theses
  - Programming, but challenging programming…
  - Focus improve speed
    - Speeding up programs (on multi-core systems)
    - Efficient Multicore Systems with Transactional Memory

That's it, have a nice vacation!