Software Fault Tolerance

Competitive Concurrency

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Overview

(Kienzle Chapter 2)

- Transactions
  - ACID properties
  - Concurrency Control
  - Recovery Support
- Flat Transactions
  - With Savepoints
- Chained Transactions
- Nested Transactions
- Split / Joint Transactions & other models
- Transactions and Exceptions

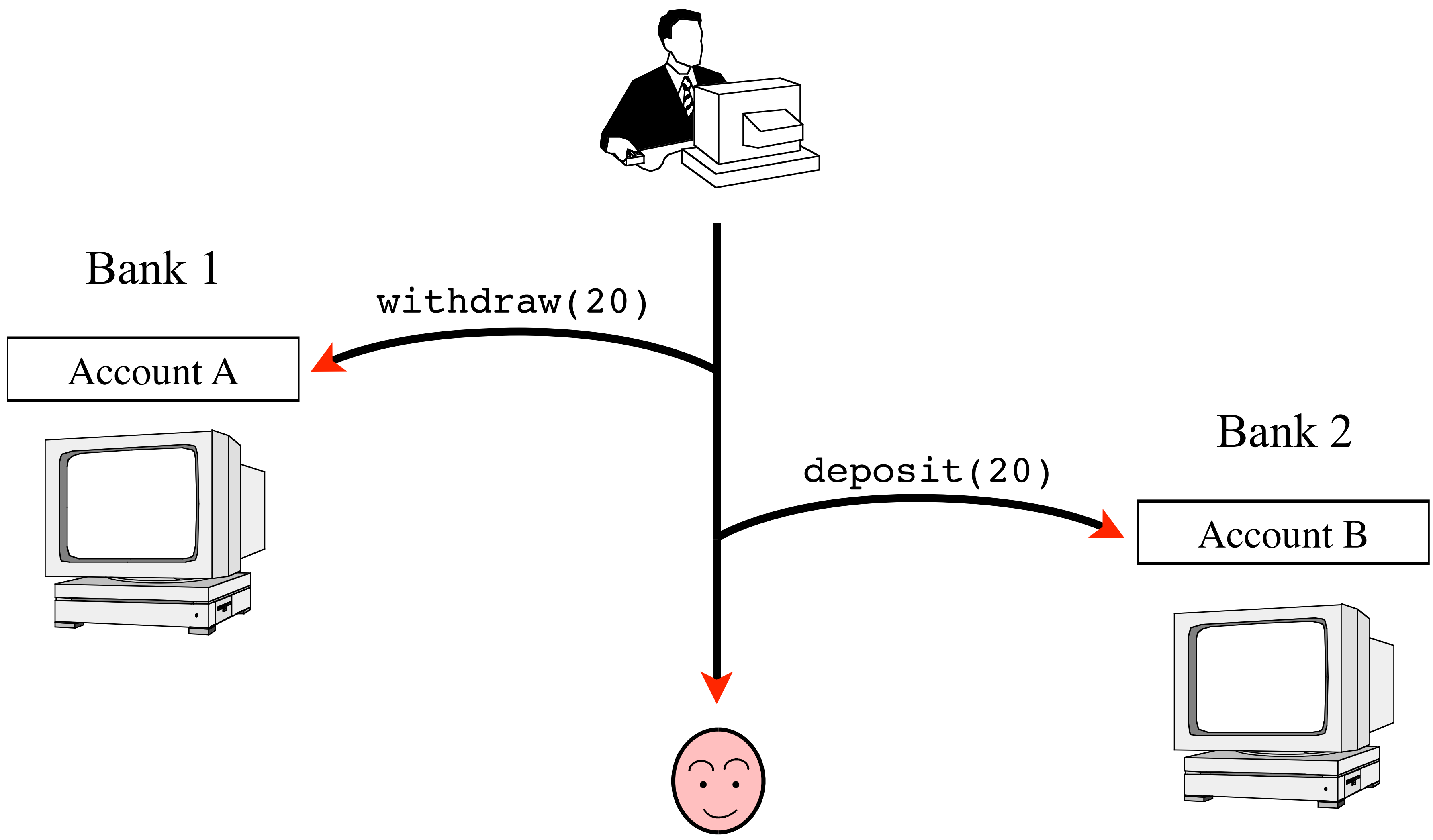
Competitive Concurrent Systems

- Processes (or threads) running in the system have been designed separately
  - Are not aware of each other
  - Do not synchronize explicitly with other processes
  - Do not communicate directly with other processes
- Each individual process
  - Does not want to be annoyed by other processes
  - Does not want to care about data consistency issues
  - Does not want to be affected by faults in other processes

ACID Properties

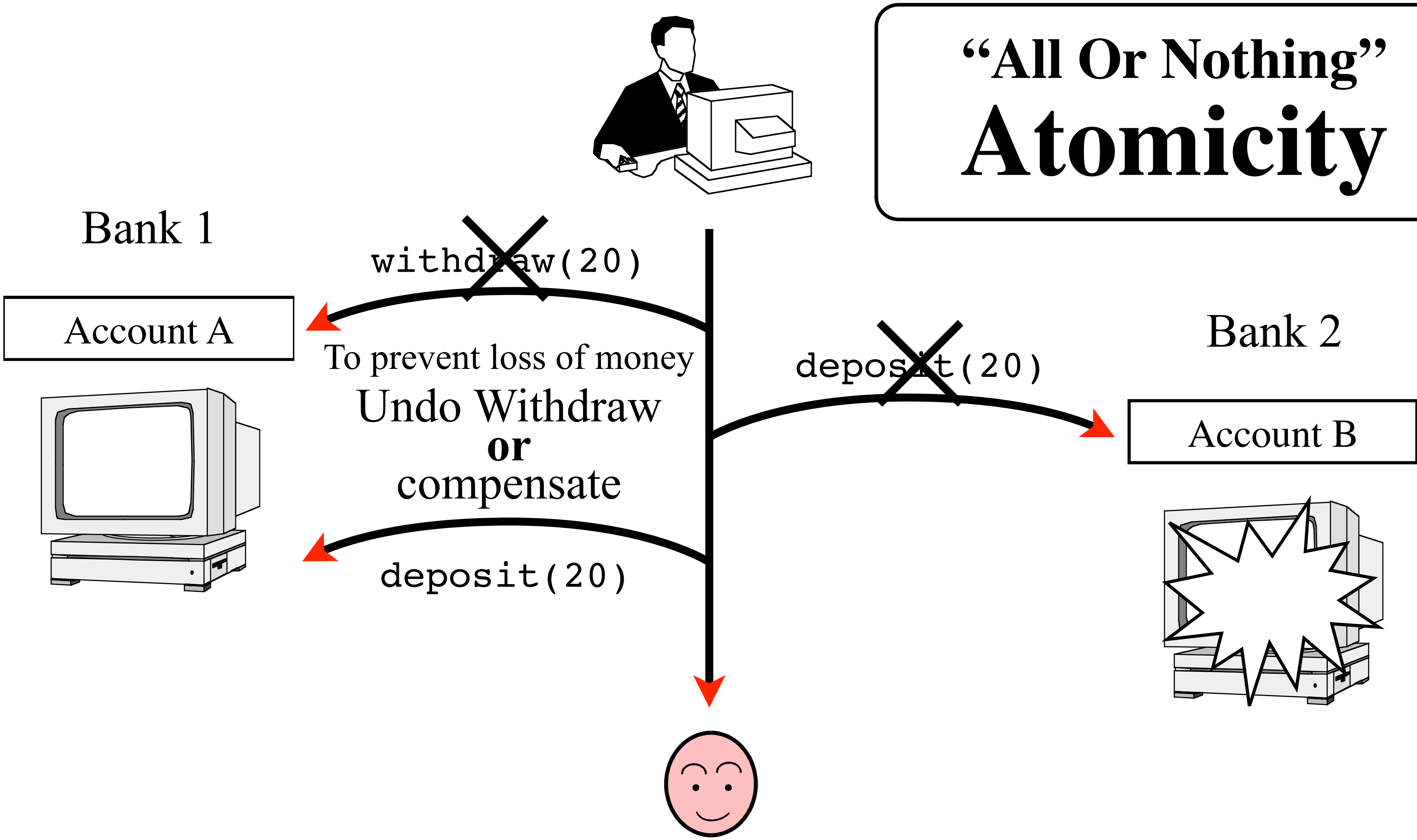
- A transaction groups together a set of operations on data objects, guaranteeing the ACID properties
  - Atomicity
  - Consistency
  - Isolation
  - Durability

A *Transfer* Operation

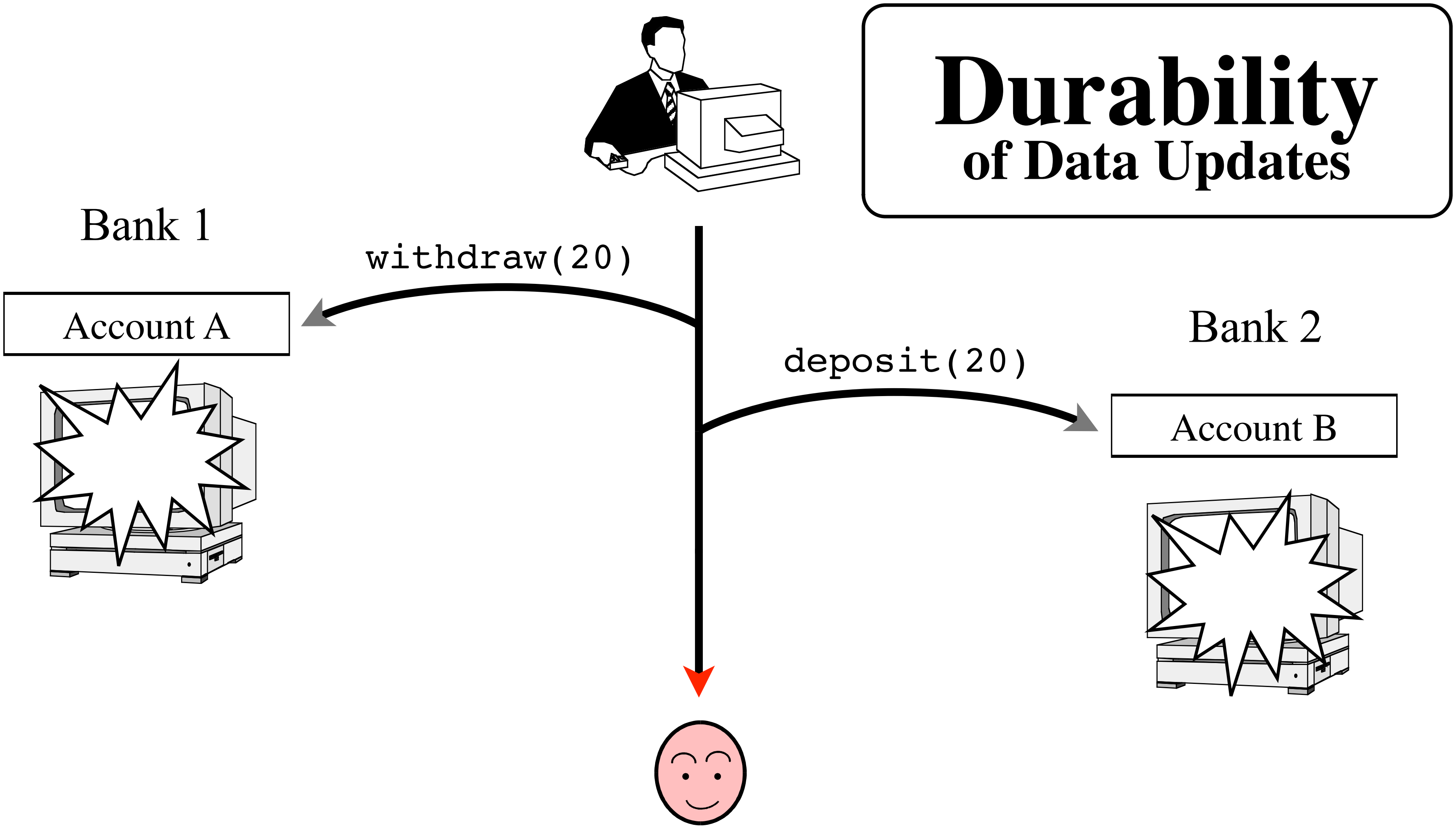


When Things go Wrong (2)

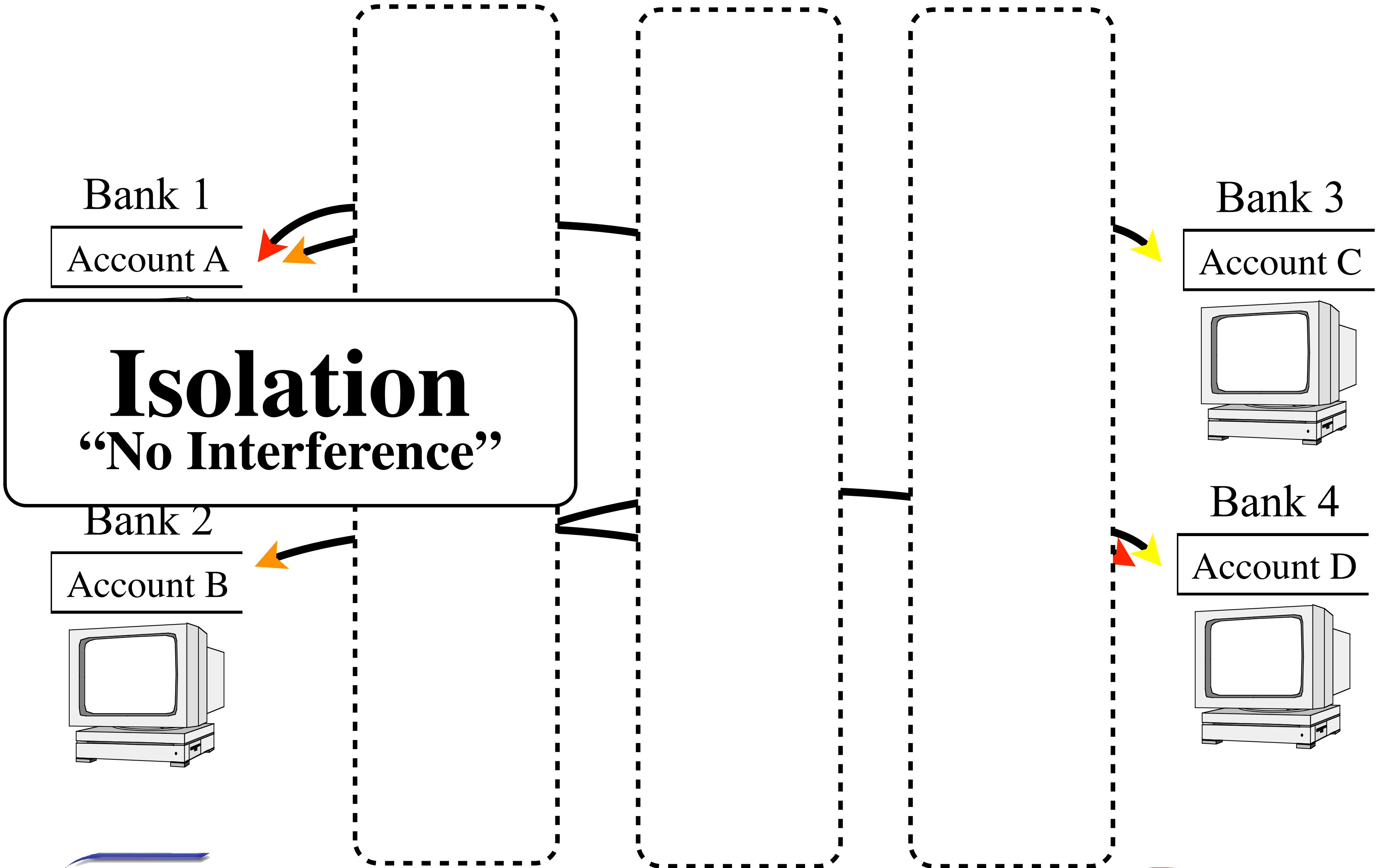
“All Or Nothing”
Atomicity



When Things go Wrong (3)



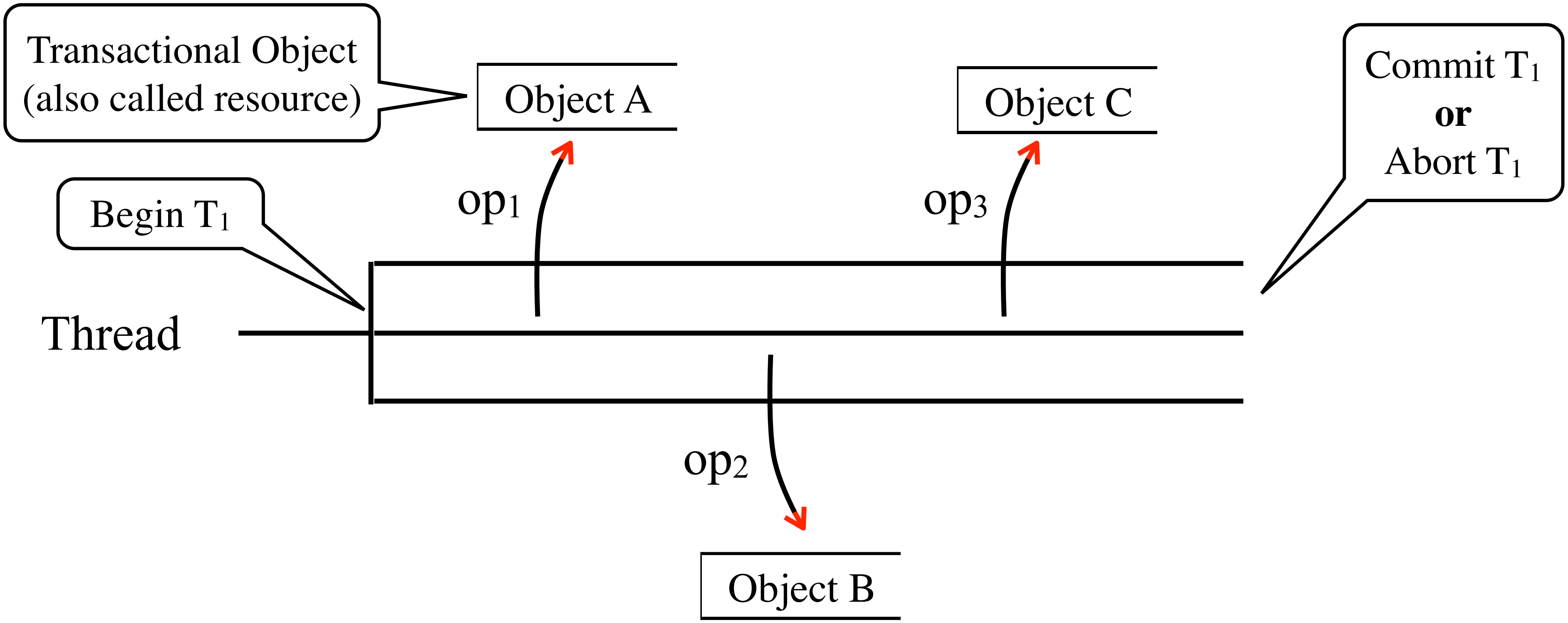
When People Work Concurrently



Consistency

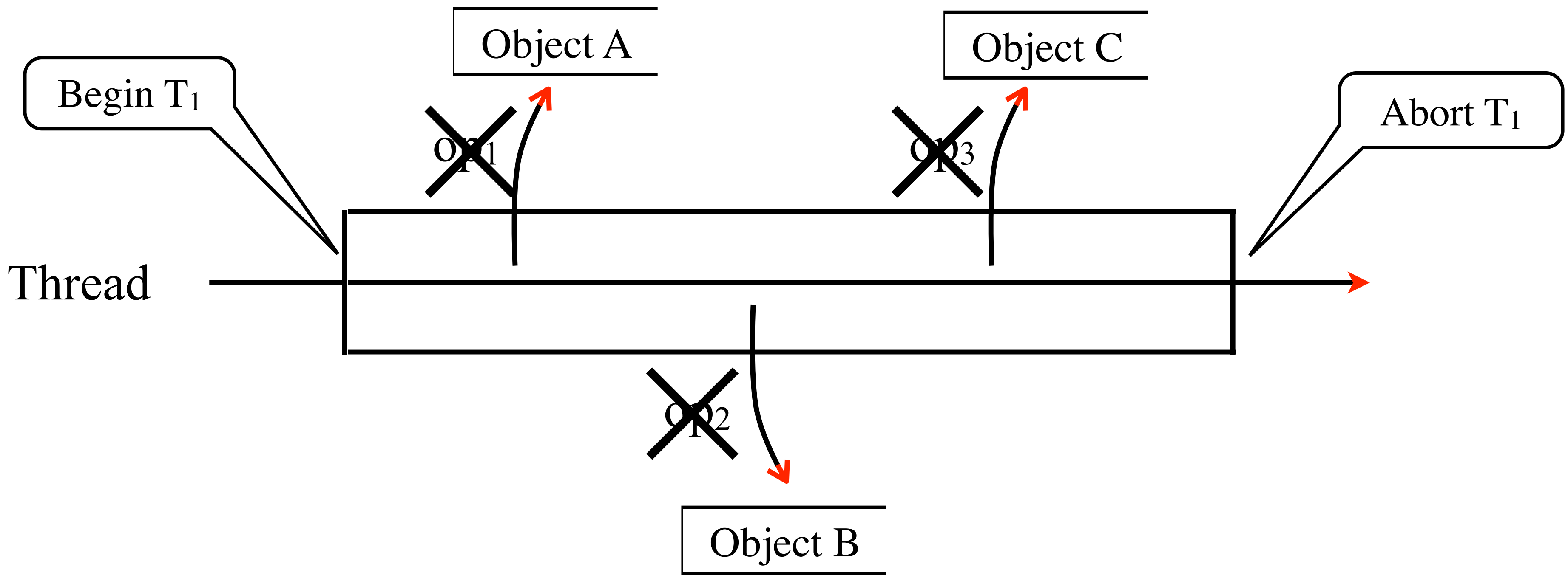
- A transaction produces consistent results only
  - Consistency criteria for the *Transfer* operation: Sum of balance of the accounts remains unchanged
- Existing transactional systems provide A, I and D
- Consistency is indirectly ensured if the transactions perform consistent state changes
  - The transaction support does not erroneously corrupt the state of the system

Flat Transactions



3 Operations: begin, commit and abort

Flat Transactions



Abort ⇒ apply backward error recovery

Serializability

Atomicity + Isolation = Serializability

The results produced by a concurrent execution of a set of transactions must be equivalent to the results produced by executing the same set of transactions sequentially, in some arbitrary order

Providing Isolation

- Concurrency control must be applied at the level of every transactional object, e.g. the accesses to a transactional object from different transactions must be monitored, making sure they do not conflict
  - Prevent transactions from seeing intermediate, possibly inconsistent state
  - Prevent the domino effect, also called cascading aborts

Conflicting Operations

- Strict concurrency control is used when no semantic knowledge of the operation is available
  - Read / write locking

	Read(y)	Write(y)
Read(x)	Yes	No
Write(x)	No	No

- If we can't tell the difference, we must assume that all operations conflict (e.g. are writers)

Semantic-based Concurrency Control

- Some operations do not conflict - they commute
- Example
  - Account with Deposit, Withdraw, Balance operations

	Deposit	Withdraw	Balance
Deposit	Yes	Yes	No
Withdraw	Yes	Yes	No
Balance	No	No	Yes

Commutativity and Update Strategy

- Commutativity actually depends on the update strategy used when modifying transactional objects
- Backward commutativity goes with in-place update
  - Op_1 commutes with Op_2, iff executing Op_1 has the same effect (final object state and return value) as executing Op_2, then Op_1, and then undoing Op_2
  - Not symmetric!
- Forward commutativity goes with deferred update
  - Op_1 commutes with Op_2, iff the return values of executing Op_1 are the same as the return values of executing Op_2 followed by Op_1

Pessimistic / Conservative CC

- Before allowing a transaction to perform an operation on a transactional object, it has to get the permission to do so
- If there is a potential conflict with any other ongoing (uncommitted) transaction, access is denied
- Block / abort or notify the calling transaction

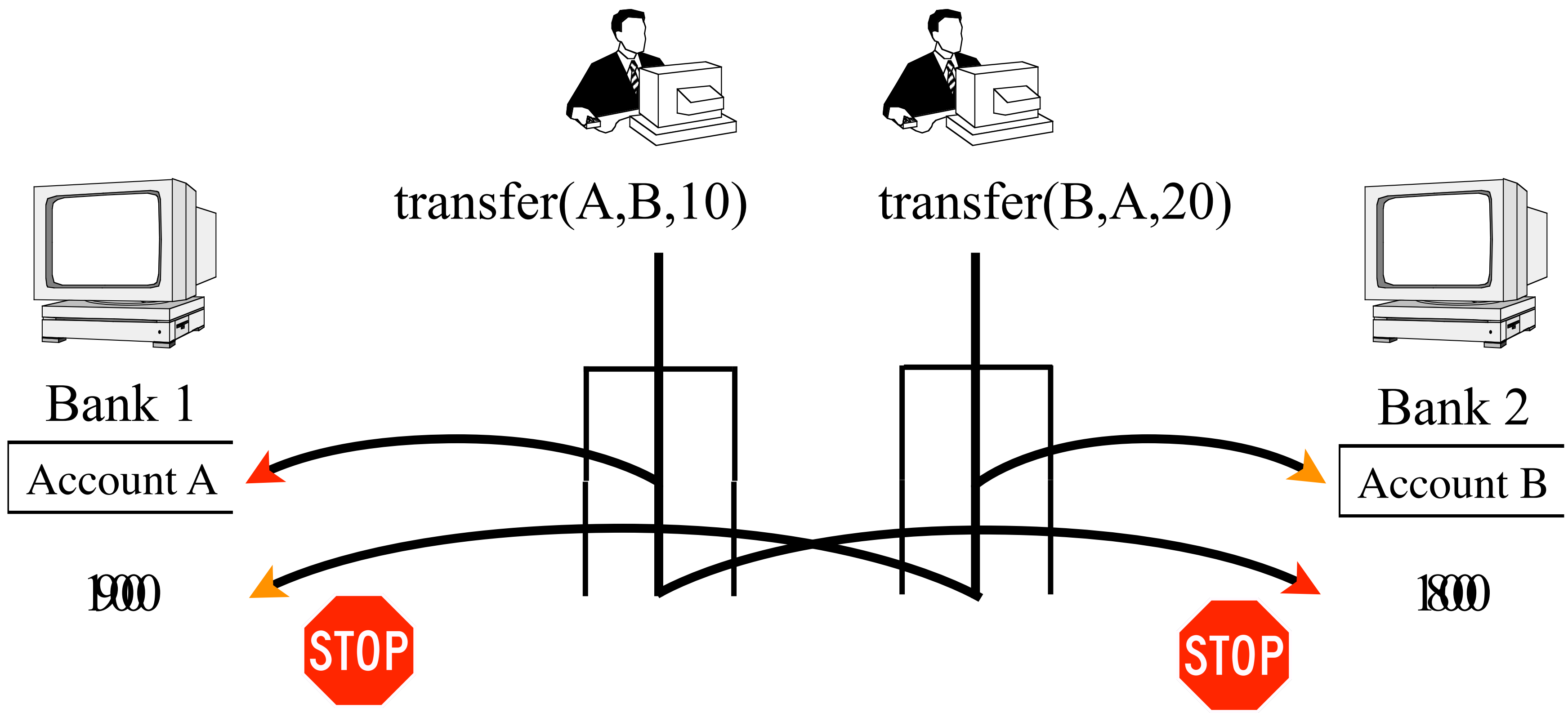
Pessimistic Example: Lock-based CC

- Before accessing a transactional object, the calling transaction must acquire the associated lock
  - If the (to be acquired) lock conflicts with any other lock held by other transactions in progress, the calling thread is blocked
  - Otherwise, the lock is granted, and the thread can execute the operation
- 2-phase locking [EGLT76] ensures serializability
  - A transaction is not allowed to acquire new locks, once a lock has been released
    $\Rightarrow$ locks are gradually acquired during execution and released only upon transaction abort or commit

Deadlocks

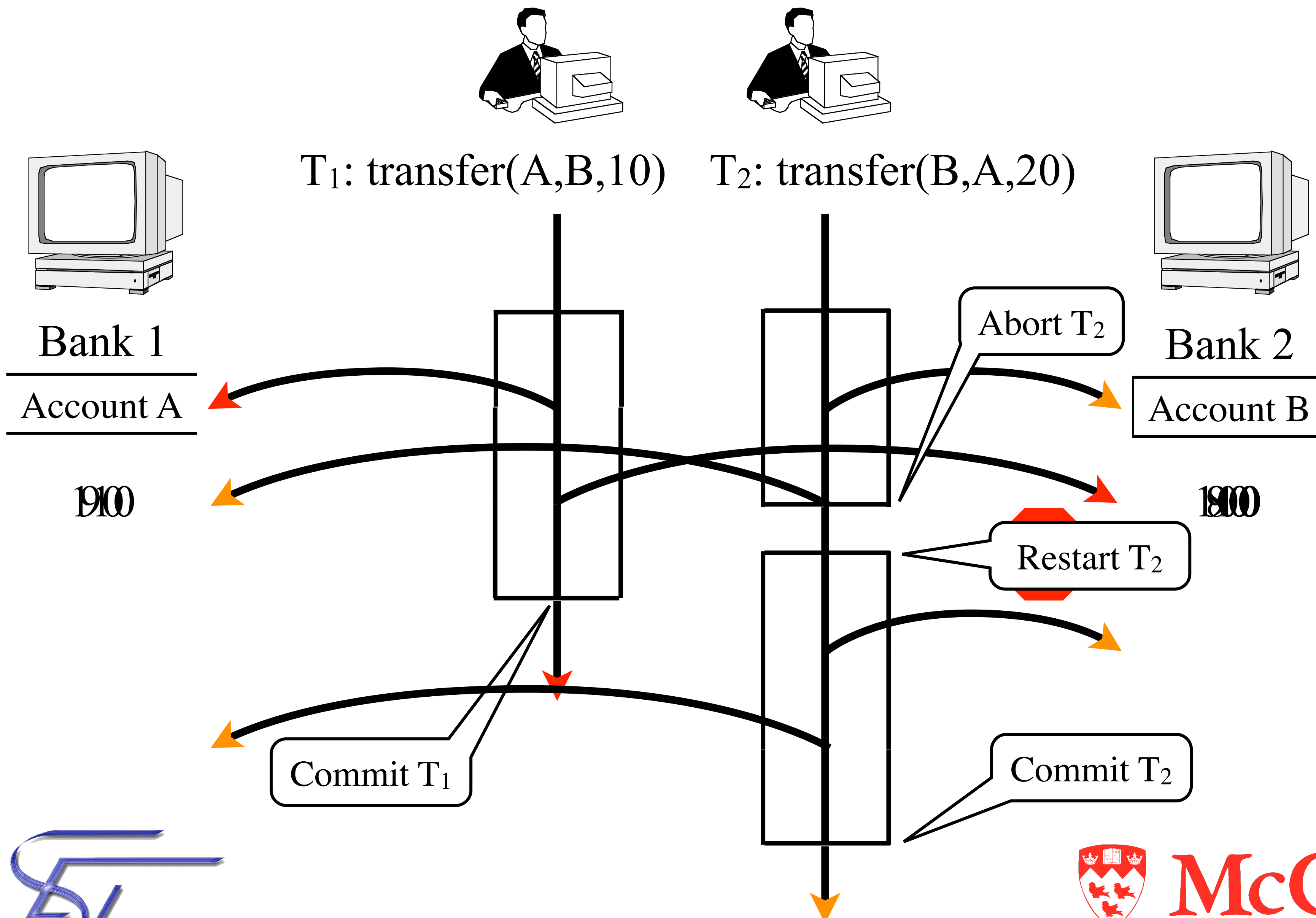
- Pessimistic blocking concurrency control might lead to deadlocks because of circular dependencies
  - T1 has acquired A and waits for B
  - T2 has acquired B and waits for A
- Deadlock prevention: Transactional objects must always be acquired in the same order to avoid deadlocks
  - Not realistic
- Detected deadlocks can be broken by aborting one of the transactions
  - Maintaining wait-for graphs and (periodically) performing cycle detection
  - Time-out

Breakable Deadlock




```
void transfer(Account source, Account dest, int amount) {
   source.withdraw(amount);
   dest.deposit(amount);
}
```

Breakable Deadlock



Deadlock-free Timestamp Ordering [BG81]

- Associate a (logical) time-stamp with each transaction
  - This implicitly specifies the serialization order in case of conflict beforehand
- Process conflicting operations based on the time-stamps of the invoking transactions at the object level
  - If a transaction A attempts to execute an operation on a transactional object that conflicts with an operation executed by transaction B
    - If timestamp(A) > timestamp(B), block A
    - If timestamp(A) < timestamp(B), abort A
  - We can't abort B because B has acquired the rights already
- Deadlock free (transactions never wait for "newer" ones)

Multi-version Locking

- Idea
  - We don't want to block late read-only transactions
  - Keep a history of committed states together with the "time range" in which they were valid
- Update (write, or read/write) transactions work on the main copy and have to acquire locks as usual
  - Upon commit, a (logical) timestamp is assigned to the update transaction, and a new committed state is created, annotated with the timestamp
- Read-only transactions get a timestamp at creation time
  - Whenever they read values, they are directed to the committed state corresponding to their timestamp

Optimistic / Aggressive CC

- Transactions are allowed to perform conflicting operations on transactional objects
- Upon commit, validation ensures serializability
- Backward validation
  - Check that previously committed transactions have not invalidated the results of the current transaction
- Forward validation
  - Ensure that a committing transaction does not conflict with transactions still in progress

Backward Validation

- Remember for every operation of a transactional object
  - Last(op), the time-stamp indicating when the most recently committed transaction has called the operation
  - First(t,op), the first time transaction t has invoked the operation
- Validate transaction t iff

  $\forall$transactionalObject($\forall$calledOp($\forall$\{op' | conflict(calledOp,op')\}: Last(op') < First(t, calledOp)))
- Assumption: deferred update

Forward Validation

- Different schemes
  - If there are conflicts with other active transactions, abort the committing one
    $\Rightarrow$ might lead to wasted aborts
  - Broadcast commit [MN82]
    - Abort transactions in progress that have executed conflicting operations
- Ideal scheme depends on the application
  - Semantics of operations, frequency of use of transactional objects, etc…

Providing Atomicity and Durability

- Atomicity and durability of transactions must be ensured at all times
- Transaction abort
  - Undo the changes made on behalf of the transaction
- At any time, a machine involved in the transaction might crash
  - Make sure that the changes of committed transactions have been stored in a safe place
  - Transactions that were not committed at the time of crash are successfully aborted

Recovery Support

- Store a transaction trace (or transaction history) in a log on stable storage
  - Transaction status
  - Accessed objects
  - Performed operations
  - Checkpoints

- Upon restart of the crashed node
  - Consult the log and perform necessary cleanup operations

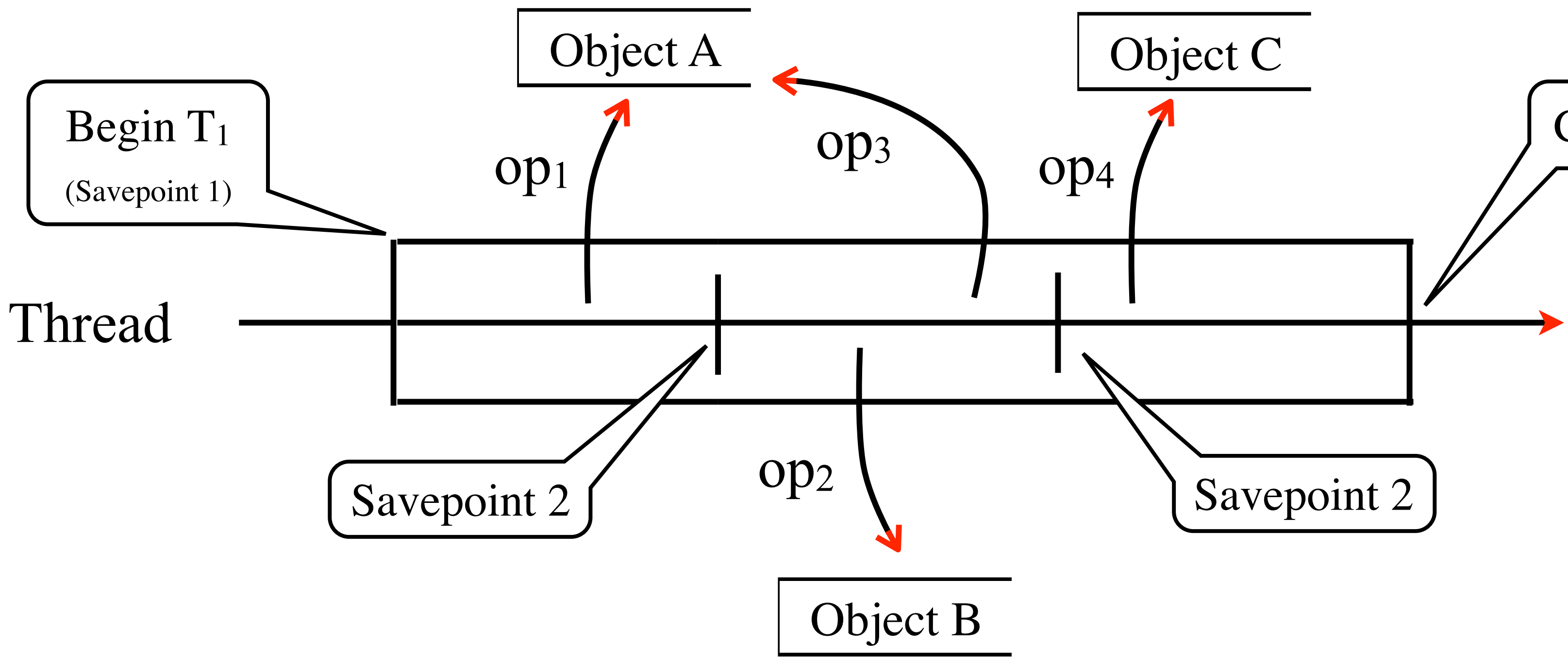
Providing Consistency

- Consistency of data is application dependent
  - There's no way the transaction support can provide consistency
- Idea:
  - Assume a consistent initial state
  - The programmer must write a transaction in such a way that it preserves consistency, i.e. moves the system from one consistent state to some other consistent state
  - Atomicity and isolation prevent inconsistencies from being visible from the outside

Other Transaction Models

- Problems with flat transactions
  - If an error is detected, flat transactions offer only two options
    - Perform manual forward error recovery (e.g. applying compensating actions, etc.)
    - Abort the transaction as a whole
  - For "long-running" transactions, giving up all results is undesirable

Flat Transactions with Savepoints (1)



Additional operations: save work and rollback work

Rollback to any savepoint is possible at any time

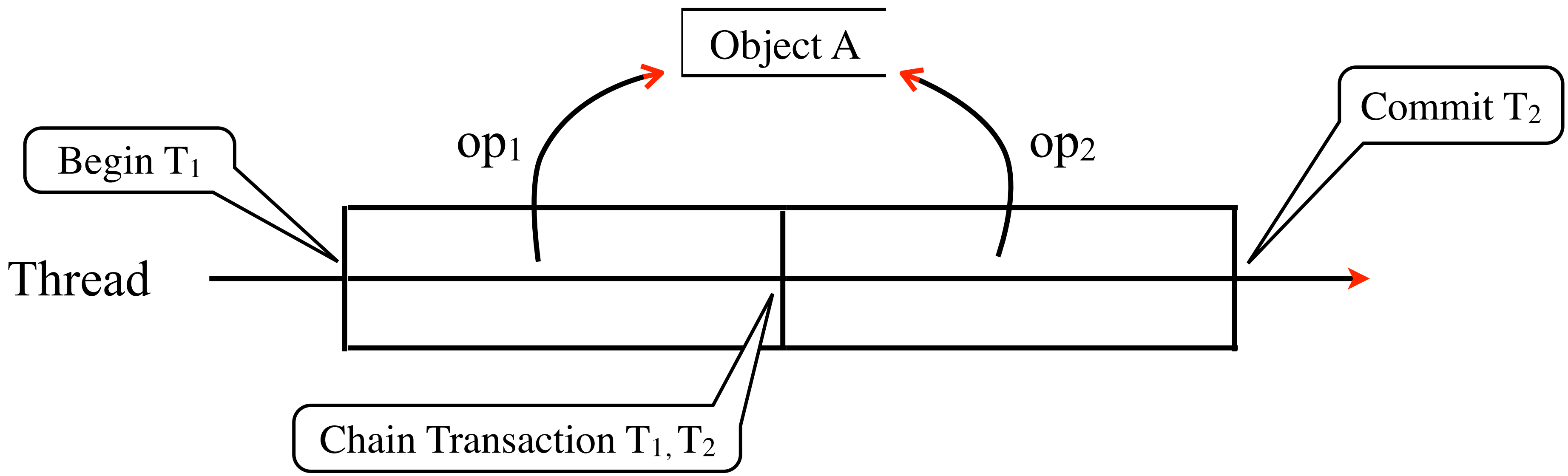
Flat Transactions with Savepoints (2)

- Additional operation Save_Work
  - Saves the state of all modified transactional objects
  - Hands back a handle to the application program
- Additional operation Rollback_Work(Handle)
  - Reestablish the state of the designated savepoint
- Begin_Transaction also establishes the first savepoint
- Aborting and rolling back to savepoint 1 are not the same operation!

Chained Transactions (1)

- In flat transactions, you still loose all work in case of a crash failure
- Chained transactions make a compromise between the flexibility of rollback and the amount of work lost after a crash
- Additional operation Chain_Transaction
  - Commit what has been done so far
  - Immediately start a new transaction with the same objects
    - Isolation property continues to hold
- Atomic “commit and begin”

Chained Transactions (2)



T_2 inherits access rights of T_1

Nested Transactions (1)

- Nested transactions [Mos81] provide functionality of transactions with savepoints, and allow recursive dynamic structuring of execution
- Transactions form a tree hierarchy
  - Top-level transactions
  - Child- or subtransactions / nested transactions
  - Leaf transactions are flat transactions

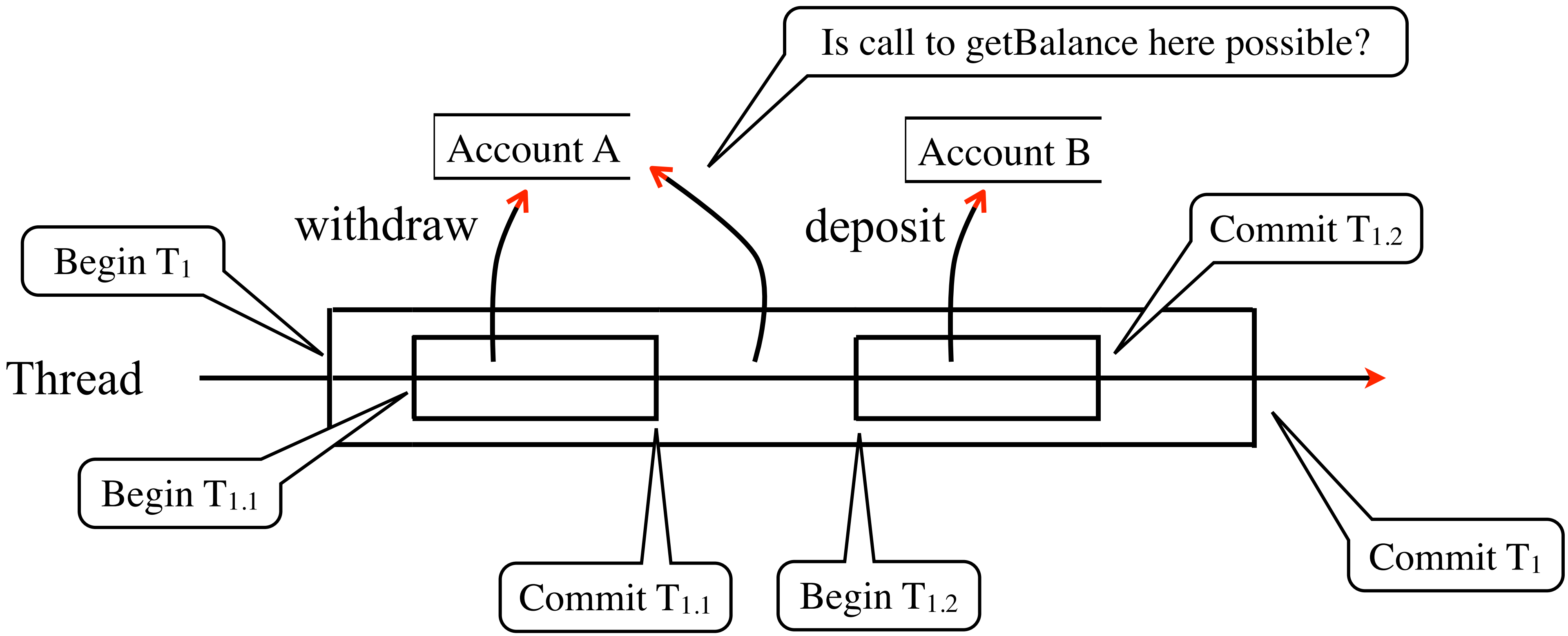
Nested Transactions (2)

- Starting nested transactions
  - Starting a new transaction from within a transaction creates a subtransaction
- Concurrency control
  - Accesses to transactional objects from inside a nested transaction are isolated with respect to the parent transaction, the sibling transactions, and other transactions
  - Access rights of the parent transaction can be “claimed” by the child

Nested Transactions (3)

- Ending nested transactions
  - A parent can only commit if all of its subtransactions have ended
  - The commit of a subtransaction makes its results visible only to the parent transaction (e.g. the parent transaction "inherits" the access rights of all transactional objects acquired by the child)
  - Aborting a nested transaction results in aborting all containing subtransactions
- Properties of non top-level transactions
  - Atomic with respect to the parent, consistency preserving with respect to the local function they implement, isolated from siblings and other external transactions, not durable

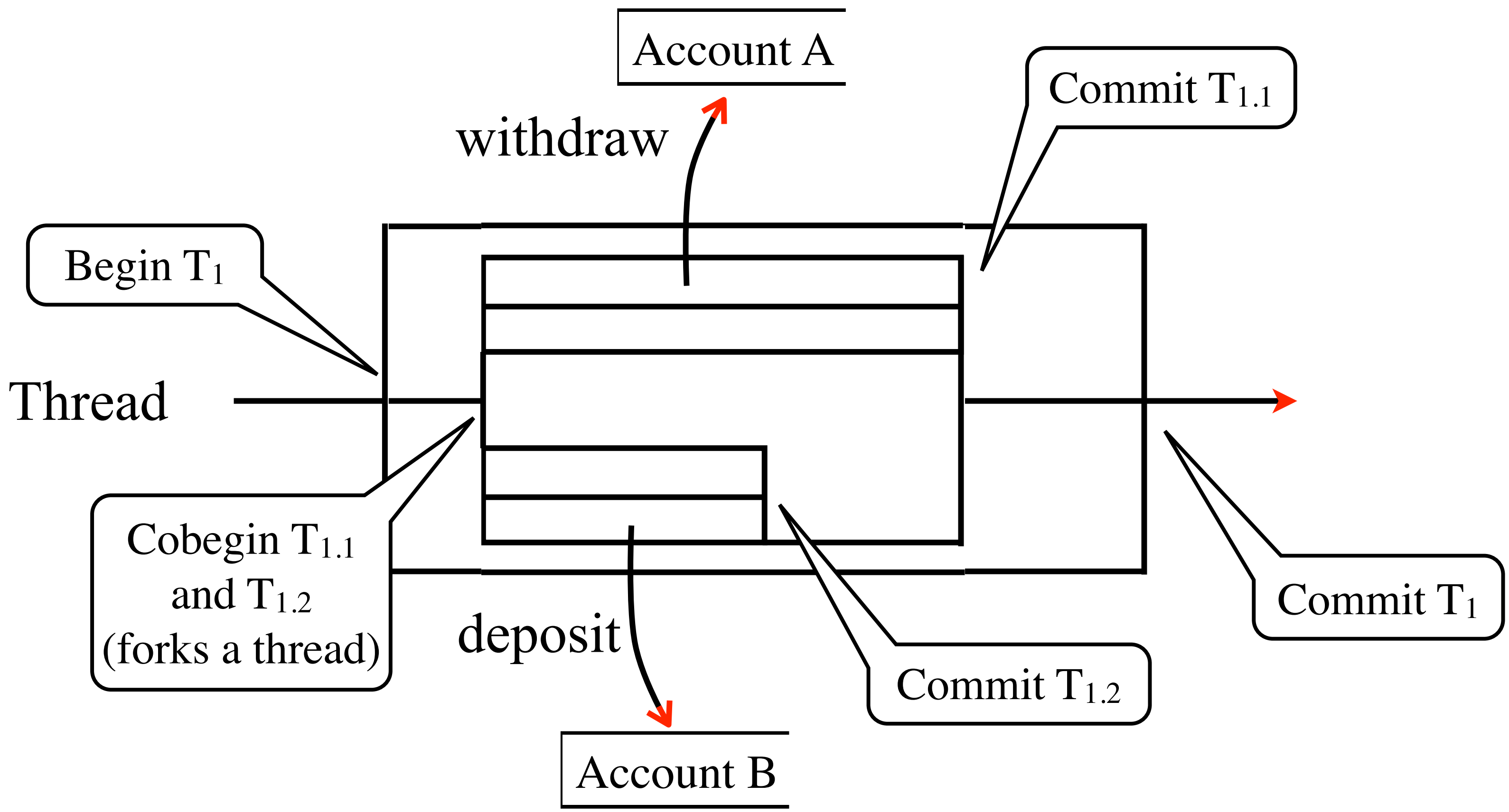
Nested Transactions (4)



Concurrent Nested Transactions

- Up to this point, all models used a single thread to execute operations on transactional objects
- Sibling transactions are isolated from each other
  - If there is no semantic dependency, they can execute in parallel to enhance performance
  - Additional threads are needed
  - Transactions themselves are still sequential!

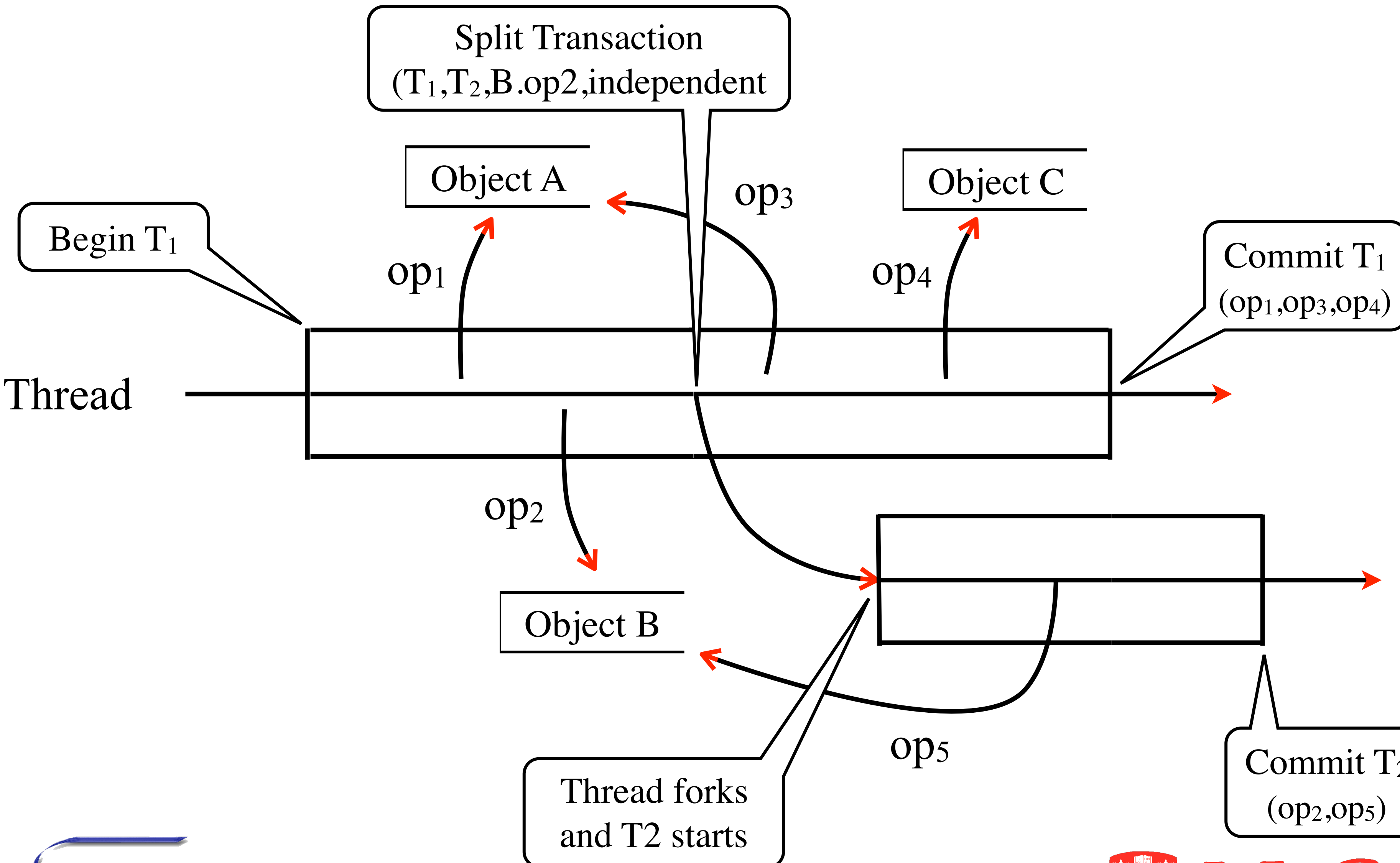
Nested Concurrent Transactions



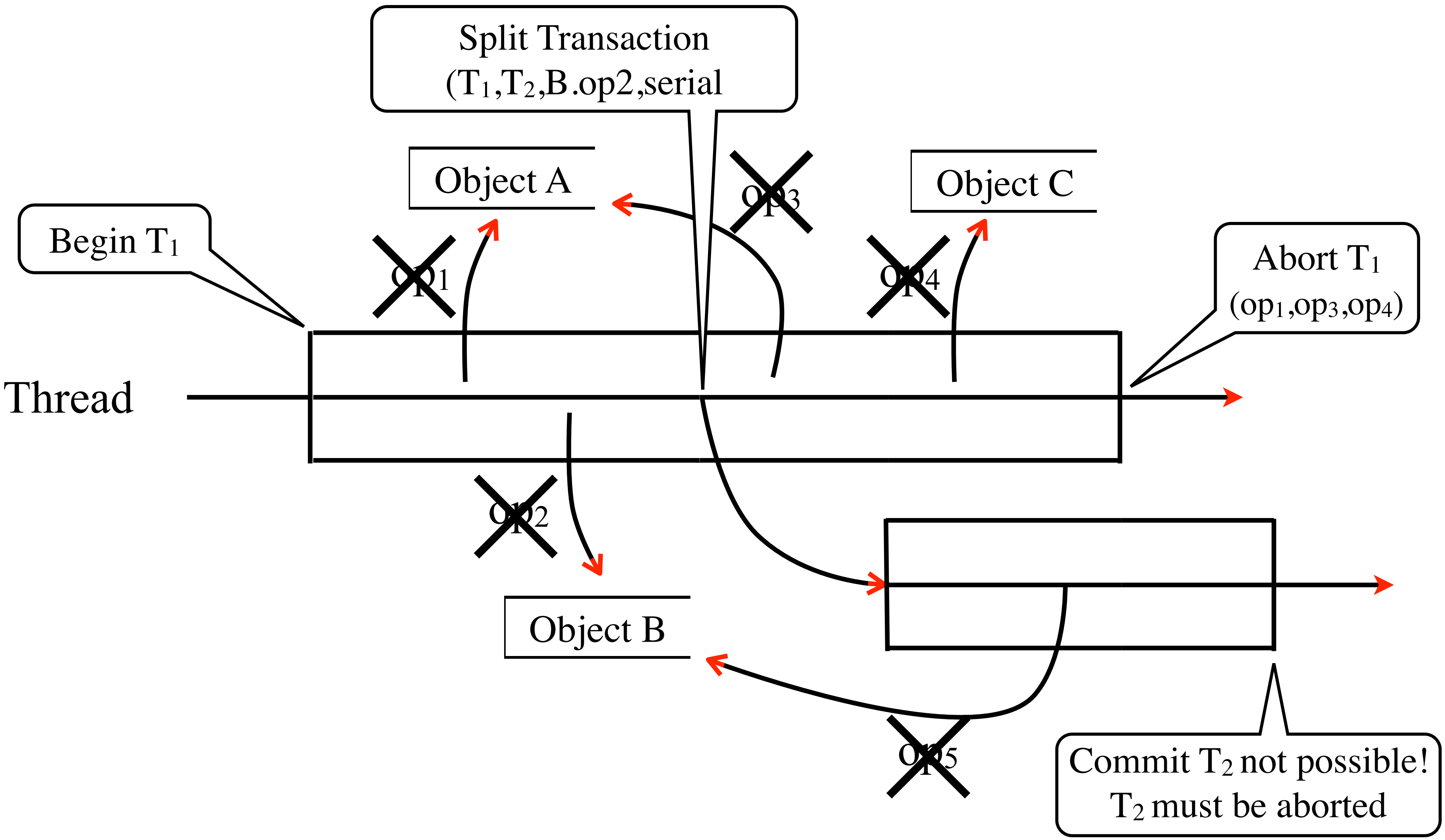
Split / Joint Transactions [PKH88]

- Split transactions
  - At any time, a transaction can split, forking a new thread and a new split-off transaction
  - At split-time, responsibility and access rights for already executed operations can be passed to the split-off transaction
  - Depending on conflicts, the split may be serial or independent
- Joint transactions
  - Instead of committing or aborting, a transaction can join another transaction, handing over all its operations and access rights

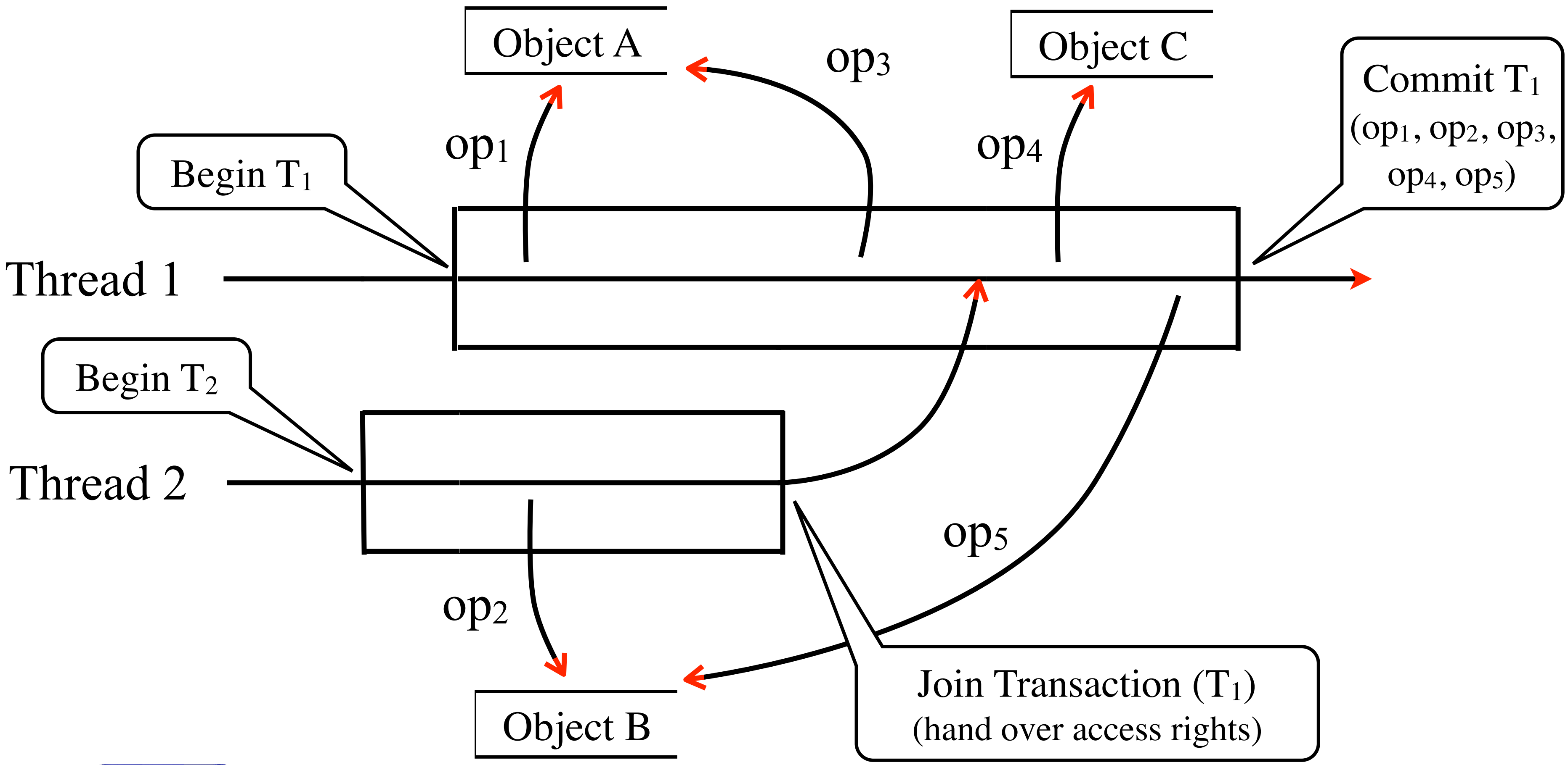
Splitting a Transaction (1)



Splitting a Transaction (2)



Joining a Transaction



Other Models

- Recoverable Communicating Actions [VRS86]
  - Transactions can communicate results to other transactions
  - Sender aborts ⇒ Receiver aborts
  - Receiver can commit iff Sender commits
- SAGAS [GMS87]
  - A saga is a set of related transactions with a specified execution order
  - Every component transaction has an associated compensating transaction
  - ACID properties guaranteed at the transaction level
  - SAGAS execute entirely or not at all

Transactions and Software Fault Tolerance

- Transactions introduced 35 years ago
- Origin in databases [GR93]
  - Handle concurrent updates of data
  - Provide tolerance of hardware failures
- Software fault tolerance
  - Provide support for backward error recovery
  - Isolation property prevents the domino effect
  - Transaction boundaries coincide with consistent state
  - Powerful if combined with structured exception handling

Transactions and Exceptions

- A & I properties allow transactions to confine erroneous state
- Exceptions signal abnormal situations or potential erroneous state
- Idea
  - Make transactions exception handling contexts
  - Add an acceptance test before transaction commit
  - Write self-checking transactional objects [KRS01]
    - Treat unhandled exceptions crossing the transaction border as abort votes

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