Data Intensive Systems (DIS)
KBH-SW7 E25

3. Distributed Databases

AALBORG
UNIVERSITY

Agenda

- Introduction
  - Heterogeneous and Homogeneous Databases
- Distributed Data Storage
- Distributed Query Processing and Optimization
- Distributed Transactions

Distributed Database System

- A distributed database system consists of loosely coupled sites that share no physical component.
- Database systems that run on different *sites* are independent of each other.
- Transactions and queries may access data at one or more sites.

Parallel DB vs. Distributed DB

- Parallel Databases
  - Machines are physically close to each other, e.g., same server room
  - Machines connect with dedicated high-speed LANs and switches, and thus communication cost is assumed to be small
  - Can share memory, share disk, or share nothing
- Distributed Databases
  - Machines can be far away from each other, e.g., in different continents
  - Can be connected using public-purpose network, e.g., Internet
  - Communication cost and problems cannot be ignored
  - Usually built using shared-nothing architecture

Distributed Databases

- In a **homogeneous** distributed database
  - All sites have identical software
  - All sites are aware of each other and agree to cooperate in processing user requests.
  - Each site surrenders part of its autonomy in terms of right to change schemas or software.
  - Appears to user as a single system.
- In a **heterogeneous** distributed database
  - Different sites may use different schemas and software.
    - Difference in schema is a major problem for query processing.
      - Data integration, schema matching
    - Difference in software is a major problem for transaction processing.
  - Sites may not be aware of each other and may provide only limited facilities for cooperation in transaction processing.

Agenda

- Introduction
- Distributed Data Storage
- Distributed Query Processing and Optimization
- Distributed Transactions

Distributed Data Storage

- Distributed Database Design:
  - How should the database and applications on top of it be place *across the sites*?
  - We assume relational data model, but the techniques can be applicable to others.
- Replication
  - System maintains multiple copies of data, stored in different sites, for **faster retrieval** and **fault tolerance**.
- Fragmentation (partitioning)
  - A relation is partitioned into several fragments stored in distinct sites.
- Replication and fragmentation can be combined.
  - Relation is partitioned into several fragments: system maintains several identical replicas of each such fragment.

Data Replication

- A relation or fragment of a relation is **replicated** if it is stored redundantly in two or more sites.
- **Full replication** of a relation is the case where the relation is stored at all sites.
- **Fully redundant** databases are those in which every site contains a copy of the entire database.
- Advantages of Replication
  - **Availability**: failure of site containing relation *r* does not result in unavailability of *r* if replicas exist.
  - **Parallelism**: queries on *r* may be processed by several sites in parallel.
  - **Reduced data transfer**: relation *r* is available locally at each site that has a replica of *r*.

Data Replication, cont.

- Disadvantages of Replication
  - Increased cost of updates
    - Each replica of relation *r* must be updated.
  - Increased complexity of concurrency control
    - Concurrent updates to distinct replicas may lead to inconsistent data unless special concurrency control mechanisms are implemented.
      - E.g., consider money transfer between replicates on different sites.
      - One solution: choose one copy as **primary copy** and apply concurrency control operations on primary copy

Data Fragmentation

- A relation r is partitioned into fragments $r_1, r_2, \ldots, r_n$ which contain sufficient information to reconstruct relation r.
- Horizontal fragmentation: each tuple of r is assigned to one or more fragments
- Vertical fragmentation: the schema for relation r is split into several smaller schemas
  - All schemas must contain a common key to ensure *lossless join property*.
  - A special attribute, e.g., the tuple-id attribute, may be added to each schema to serve as the key.

Example Relations

- Relation *account*

branch_name	account_number	balance

- Relation *employee*

account_number	balance	branch_name	customer_name

Horizontal Fragmentation of *account* Relation

branch_name	account_number	balance
Hillside	A-305	500
Hillside	A-226	336
Hillside	A-155	62

$account_1 = \sigma_{branch\_name=\text{“Hillside”}}(account)$

branch_name	account_number	balance
Valleyview	A-177	205
Valleyview	A-402	10000
Valleyview	A-408	1123
Valleyview	A-639	750

$account_2 = \sigma_{branch\_name=\text{“Valleyview”}}(account)$

Vertical Fragmentation of *employee* Relation

branch_name	customer_name	tuple_id
Hillside	Lowman	1
Hillside	Camp	2
Valleyview	Camp	3
Valleyview	Kahn	4
Hillside	Kahn	5
Valleyview	Kahn	6
Valleyview	Green	7

$$deposit_1 = \Pi_{branch\_name,\ customer\_name,\ tuple\_id}(employee)$$

account_number	balance	tuple_id
A-305	500	1
A-226	336	2
A-177	205	3
A-402	10000	4
A-155	62	5
A-408	1123	6
A-639	750	7

$$deposit_2 = \Pi_{account\_number,\ balance,\ tuple\_id}(employee)$$

Advantages of Fragmentation

- Horizontal fragmentation:
  - allows parallel processing on fragments of a relation
  - allows a relation to be split so that tuples are located where they are most frequently accessed
- Vertical fragmentation:
  - allows parallel processing on a relation
  - allows tuples to be split so that each part of the tuple is stored where it is most frequently accessed
  - tuple-id attribute allows efficient joining of vertical fragments
- Vertical and horizontal fragmentation can be mixed.
  - Fragments may be successively fragmented to an arbitrary depth.

Data Transparency

- Data transparency
  - Degree to which a system user may remain *unaware* of the details of *how* and *where* the data items are stored in a distributed system.
- Consider transparency issues in relation to:
  - Fragmentation transparency
  - Replication transparency
  - Location transparency

- *NB*: Similar ideas are used in distributed file systems like HDFS

Agenda

- Introduction
- Distributed Data Storage
- Distributed Query Processing and Optimization
  - Fragmented storage
  - Non-fragmented storage
- Distributed Transactions

Distributed Query Processing

- For centralized systems, the primary criterion for measuring the cost of a particular query strategy is the number of disk accesses (IOs).
- In a distributed system, other issues must be considered:
  - Data transmission cost over the network (often critical).
  - The potential gain in performance: several sites process parts of the query in parallel.
- Translating algebraic queries on fragments
  - It must be possible to construct relation *r* from its fragments.
  - Replace relation *r* by the expression to construct relation *r* from its fragments.

Query Transformation Example

- Consider the horizontal fragmentation of the *account* relation

  $account_1 = \sigma_{\ branch\_name\ =\ \text{“Hillside”}} (account)$

  $account_2 = \sigma_{\ branch\_name\ =\ \text{“Valleyview”}} (account)$

- The query $\sigma_{\ branch\_name\ =\ \text{“Hillside”}} (account)$ becomes

  $\sigma_{\ \text{branch\_name} = \text{“Hillside”}} (account_1 \cup account_2)$

  which is optimized into

  $\sigma_{\ branch\_name\ =\ \text{“Hillside”}} (account_1) \cup \sigma_{\ branch\_name\ =\ \text{“Hillside”}} (account_2)$

  - Since $account_1$ has only tuples of the Hillside branch, we can eliminate the selection operation.
  - Apply the definition of $account_2$ to obtain

    $\sigma_{\ branch\_name\ =\ \text{“Hillside”}} (\sigma_{\ branch\_name\ =\ \text{“Valleyview”}} (account))$

    - This expression always gives an empty set.
- Finally, the Hillside site returns its whole $account_1$ as the result of the query.

Reduced Query due to Fragmentation

Two relations with corresponding schemas:

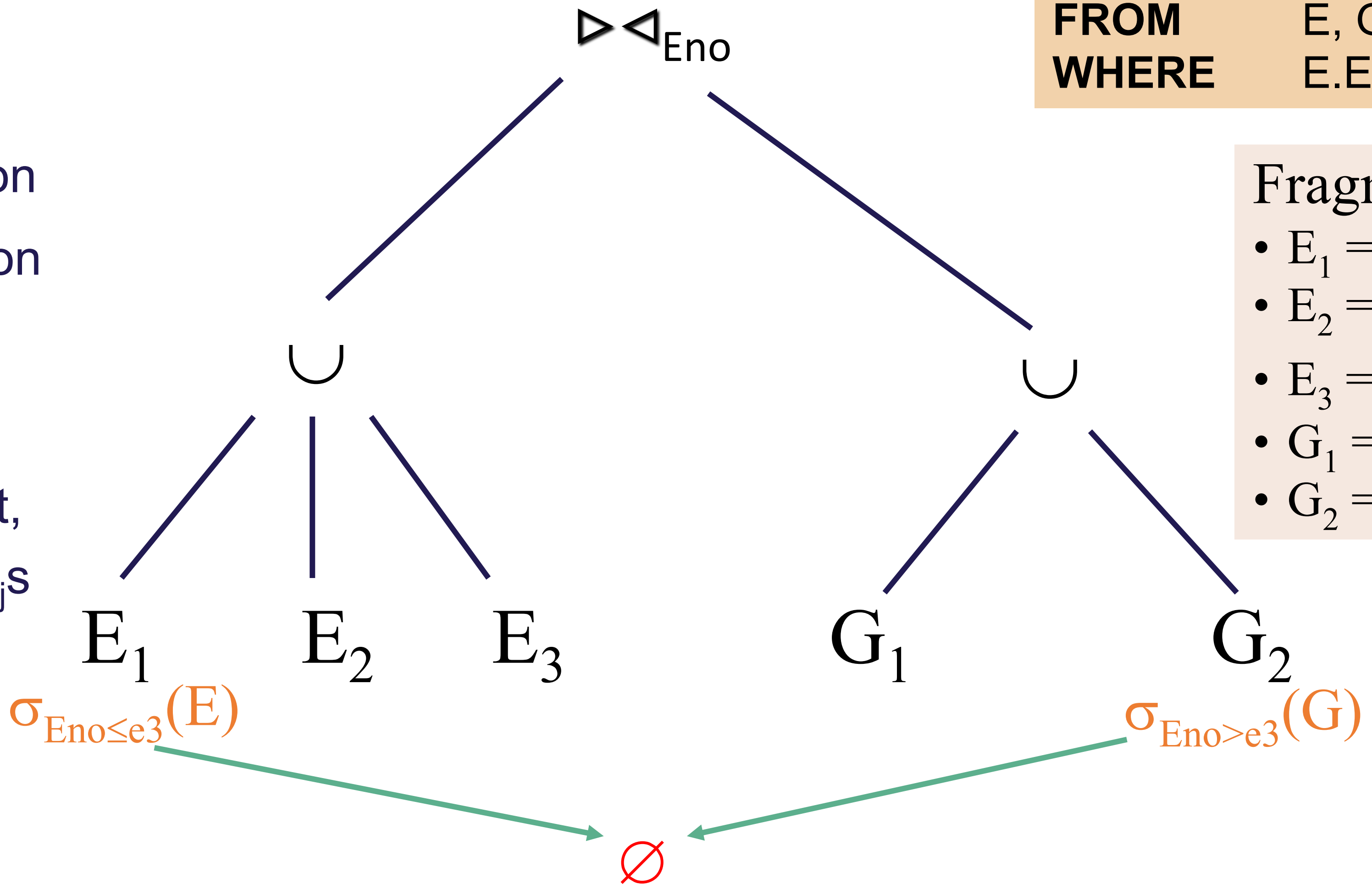
E(Eno, Ename, Title) **G(Eno, Jno, Resp, Dur)**

- E is *horizontally* fragmented into E_1, E_2 and E_3 as follows:
  - $E_1 = \sigma_{Eno \le e3}(E)$
  - $E_2 = \sigma_{e3 < Eno \le e6}(E)$
  - $E_3 = \sigma_{Eno > e6}(E)$
- G is *horizontally* fragmented into G_1 and G_2 as follows:
  - $G_1 = \sigma_{Eno \le e3}(G)$
  - $G_2 = \sigma_{Eno > e3}(G)$
- Consider the following *natural join* query-1:

```
SELECT *
FROM   E, G
WHERE E.Eno = G.Eno
```

Query Tree for query-1:

- Steps
  1. Get E by union
  2. Get G by union
  3. Join E and G
- Steps 1 and 2 can be parallelized. But, not all E_is match G_js



SELECT	*
FROM	E, G
WHERE	E.Eno = G.Eno

Fragments
- $E_1 = \sigma_{Eno \le e3}(E)$
- $E_2 = \sigma_{e3 < Eno \le e6}(E)$
- $E_3 = \sigma_{Eno > e6}(E)$
- $G_1 = \sigma_{Eno \le e3}(G)$
- $G_2 = \sigma_{Eno > e3}(G)$

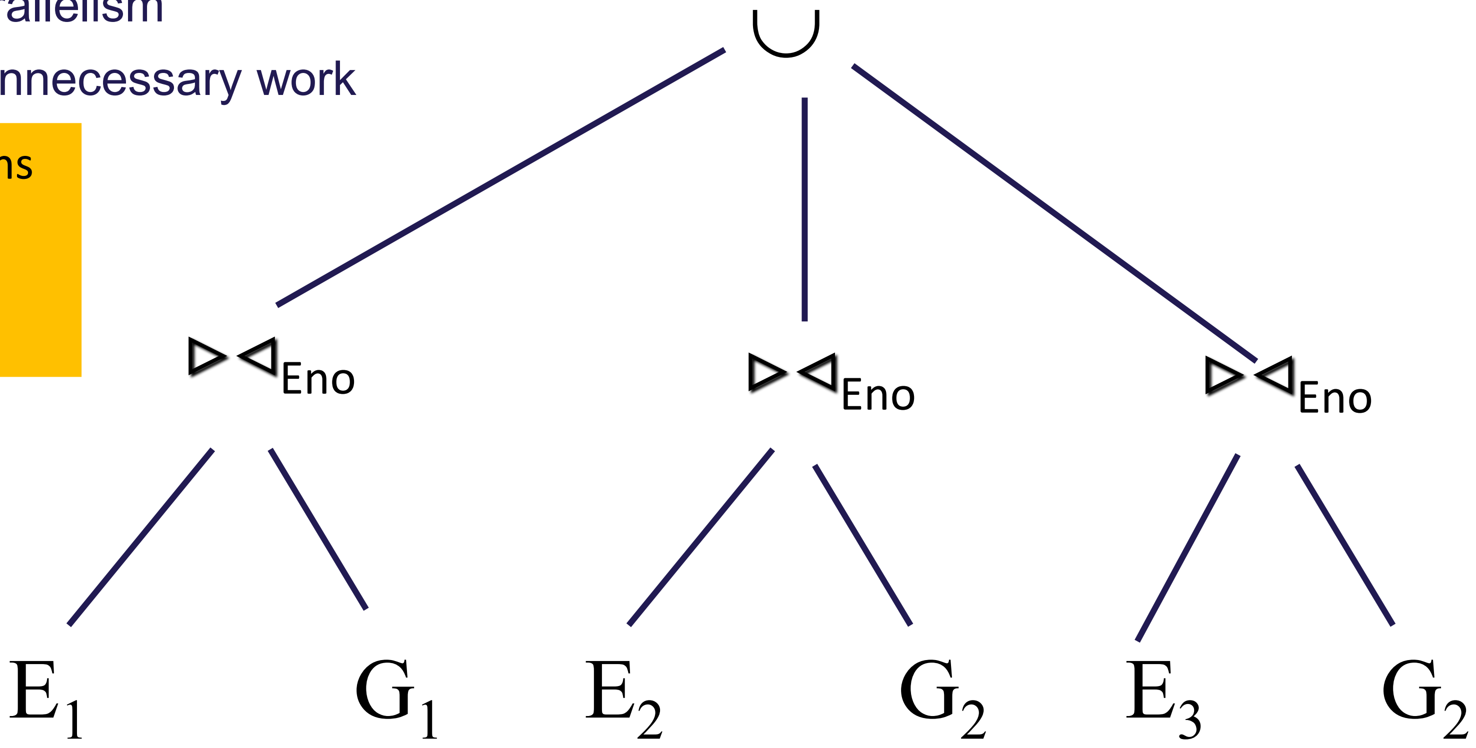
Empty joins
- $E_1 \bowtie G_2$
- $E_2 \bowtie G_1$
- $E_3 \bowtie G_1$

Reduced Query Tree for query-1:

- Advantages of the reduced query tree:
  - Provide parallelism
  - Eliminate unnecessary work

Empty joins
- $E_1 \bowtie G_2$
- $E_2 \bowtie G_1$
- $E_3 \bowtie G_1$

```
SELECT   *
FROM     E, G
WHERE    E.Eno = G.Eno
```



Fragments
- $E_1 = \sigma_{Eno \leq e3}(E)$
- $E_2 = \sigma_{e3 < Eno \leq e6}(E)$
- $E_3 = \sigma_{Eno > e6}(E)$
- $G_1 = \sigma_{Eno \leq e3}(G)$
- $G_2 = \sigma_{Eno > e3}(G)$

Another Reduced Query Example

E(Eno, Ename, Title) **G(Eno, Jno, Resp, Dur)**

Fragmentation is as follows:

$E_1 = \sigma_{Title='Programmer'}(E)$

$E_2 = \sigma_{Title\neq'Programmer'}(E)$

$G_1 = G \ltimes_{Eno} E_1$: Those G records that contribute to $G \bowtie E_1$.

$G_2 = G \ltimes_{Eno} E_2$: Those G records that contribute to $G \bowtie E_2$.

Query-2:

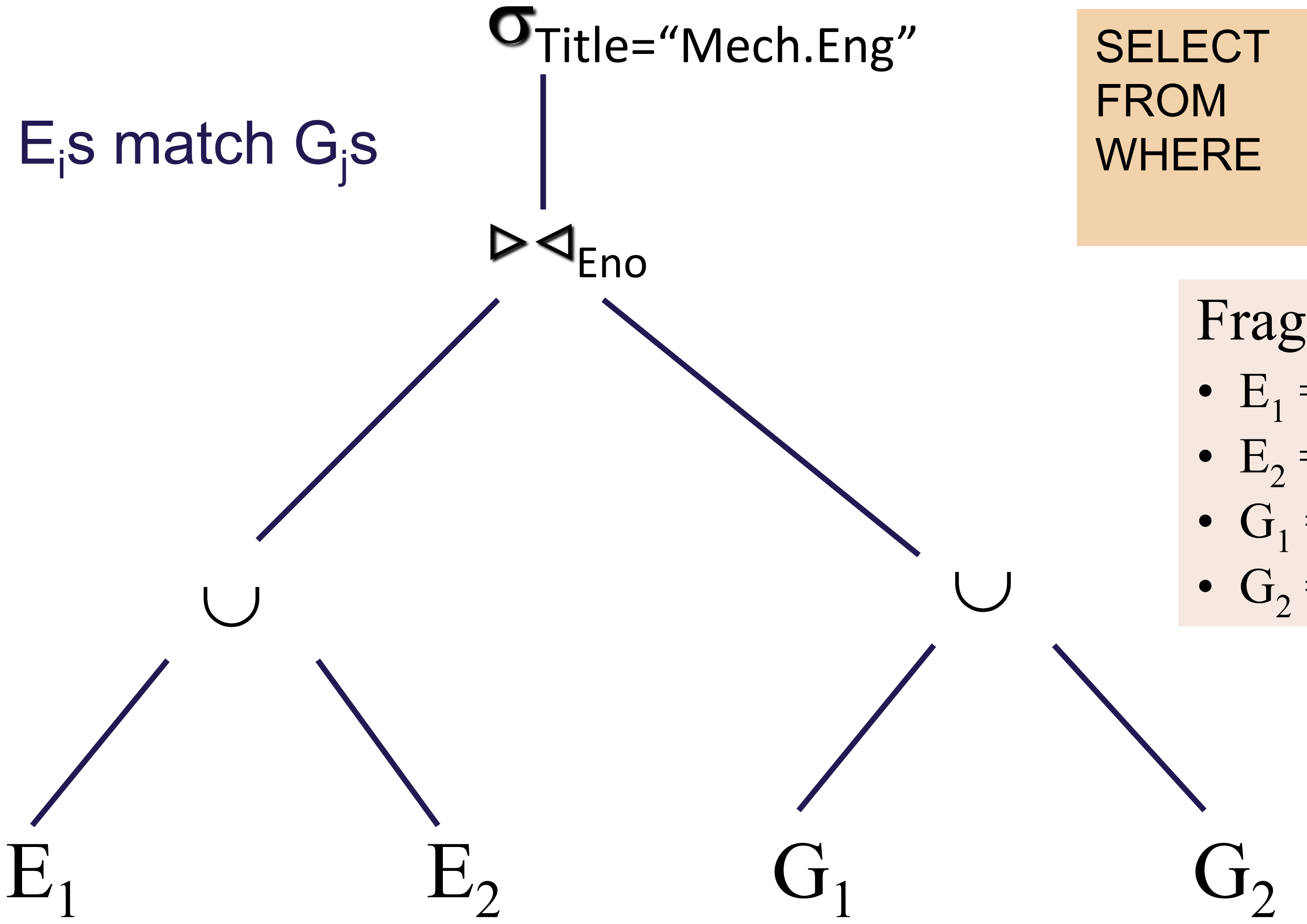
```
SELECT   *
FROM     E, G
WHERE    E.Eno = G.Eno AND
         E.Title = "Mech. Eng."
```

Left semijoin $R \ltimes S$

- The result is the set of all records in R for which there is a record in S that is equal on their common attributes.
- Unlike a natural join, the other columns of S do not appear in the result.

Query Tree for query-2:

- Again, not all E_is match G_js



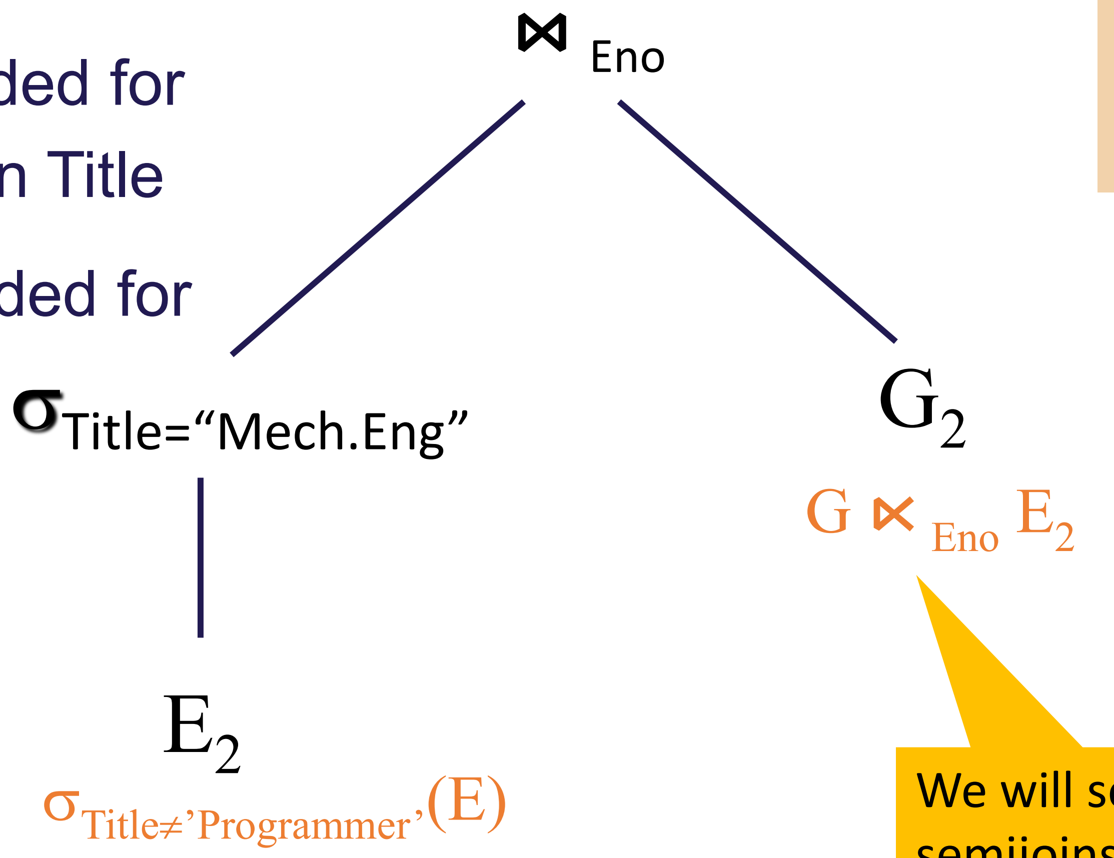

```
SELECT    *
FROM      E, G
WHERE     E.Eno = G.Eno AND
          E.Title = “Mech. Eng.”
```

Fragments

- $E_1 = \sigma_{Title=\text{'Programmer'}}(E)$
- $E_2 = \sigma_{Title\neq\text{'Programmer'}}(E)$
- $G_1 = G \ltimes_{Eno} E_1$
- $G_2 = G \ltimes_{Eno} E_2$

Reduced Query Tree for query-2:

- Only E_2 is needed for the selection on Title
- Only G_2 is needed for the join




```
SELECT  *
FROM    E, G
WHERE   E.Eno = G.Eno AND
        E.Title = "Mech. Eng."
```

Fragments

- $E_1 = \sigma_{Title=\text{'Programmer'}}(E)$
- $E_2 = \sigma_{Title\neq\text{'Programmer'}}(E)$
- $G_1 = G \ltimes_{Eno} E_1$
- $G_2 = G \ltimes_{Eno} E_2$

We will see more semijoins shortly.

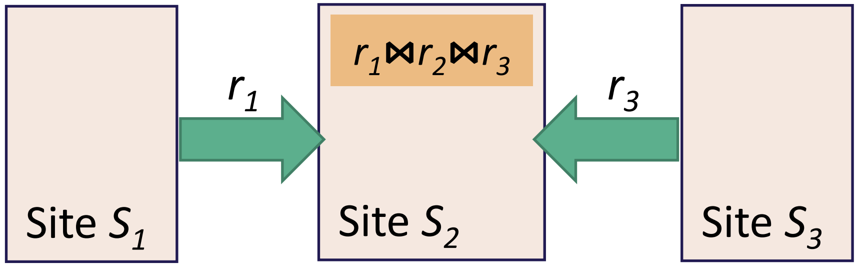
Distributed Join Processing

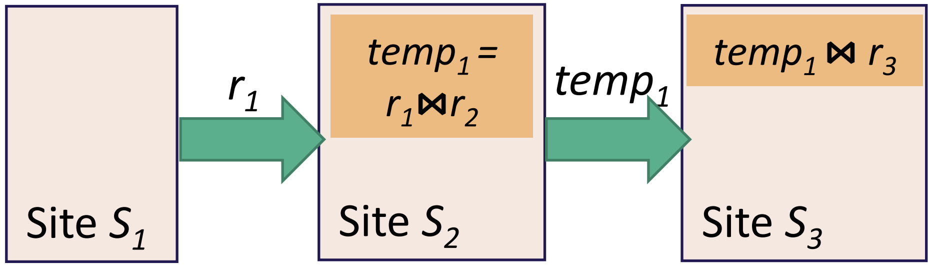
- Distributed query processing must consider following factors:
  - amount of data to be shipped between sites
  - cost of transmitting a data block between sites
  - relative processing speed at each site
- Consider the following relational algebra expression in which the three relations are *neither* replicated *nor* fragmented:

  account ⋈ *depositor* ⋈ *branch*
  - *account* is stored at site S_1
  - *depositor* at S_2
  - *branch* at S_3
- For a query issued at site S_I, the system needs to produce the result at site S_I

Simple Join Processing Strategies

- Ship copies of all three relations to site S_I and choose a strategy for processing the entire locally at site S_I. (*centralized*)
- Ship a copy of the account relation to site S_2 and compute $temp_1$ = *account* ⋈ *depositor at* S_2. Ship $temp_1$ from S_2 to S_3, and compute $temp_2 = temp_1 \bowtie branch$ at S_3. Ship the result $temp_2$ to S_I. (*serialized*)
- Similar strategies, exchanging the roles S_1, S_2, S_3.



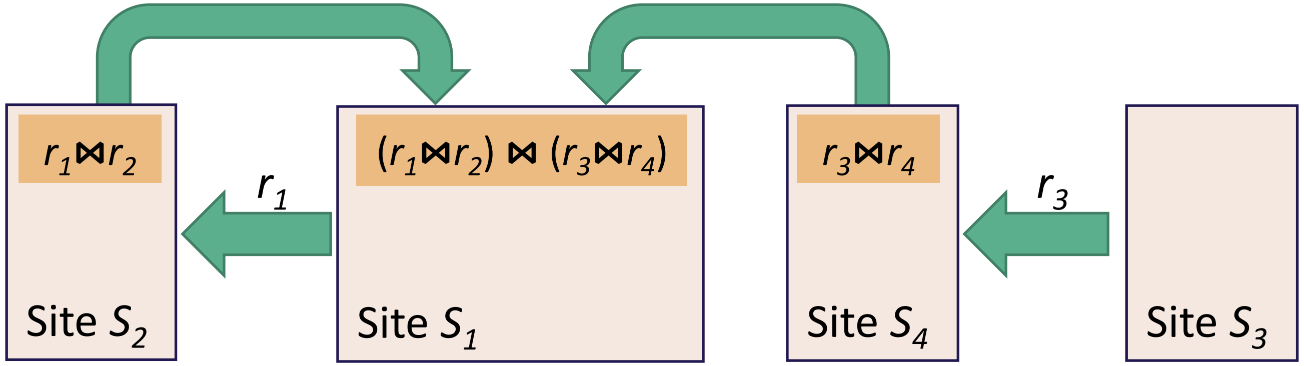


Parallel Distributed Join Strategy

Consider $r_1 \bowtie r_2 \bowtie r_3 \bowtie r_4$ where each relation r_i is stored at site S_i. Suppose the result must be presented at site S_1.

- r_1 is shipped to S_2 and $r_1 \bowtie r_2$ is computed at S_2; simultaneously, r_3 is shipped to S_4 and $r_3 \bowtie r_4$ is computed at S_4.
- S_2 sends tuples of $(r_1 \bowtie r_2)$ to S_1 *as they are being produced*;
  S_4 sends tuples of $(r_3 \bowtie r_4)$ to S_1 *as they are being produced*.
- Once tuples of $(r_1 \bowtie r_2)$ and $(r_3 \bowtie r_4)$ arrive at S_1, $(r_1 \bowtie r_2) \bowtie (r_3 \bowtie r_4)$ is computed *in parallel* with the computation of $(r_1 \bowtie r_2)$ at S_2 and the computation of $(r_3 \bowtie r_4)$ at S_4.

- Pipeline
- Parallelism



Semijoin Strategy

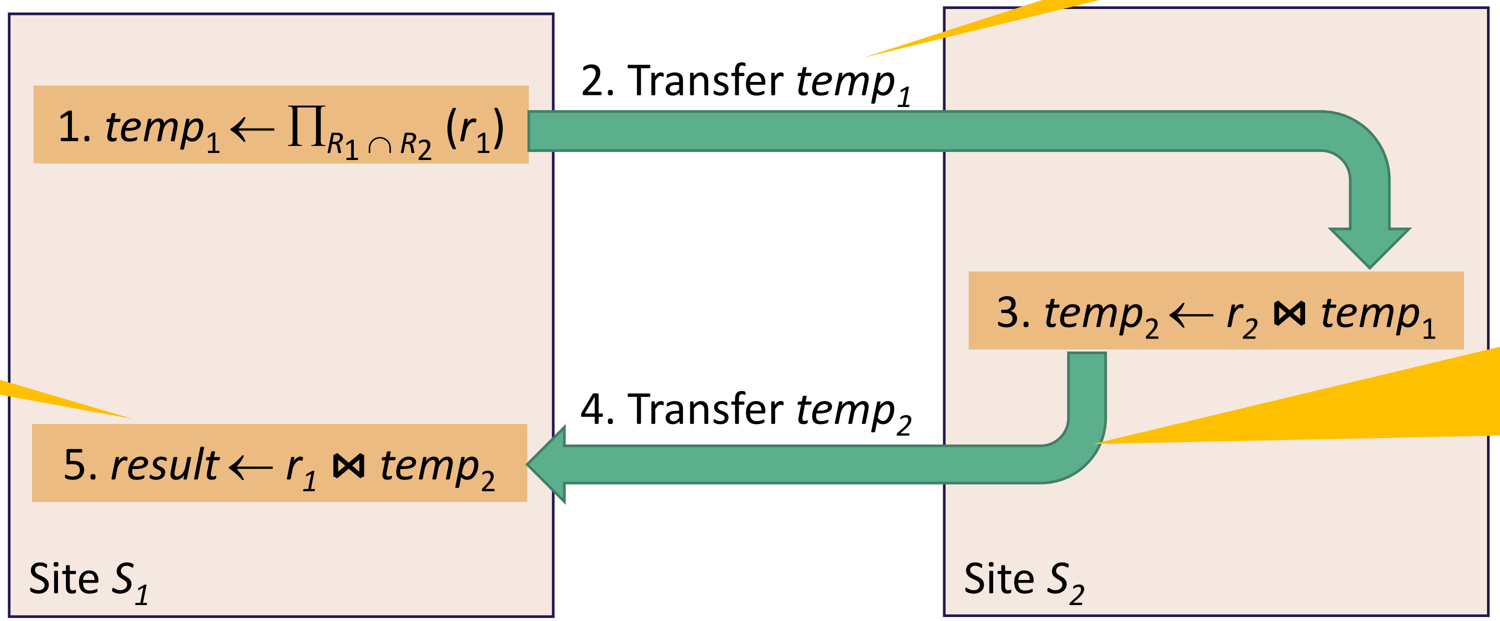
- Let r_1 be a relation with schema R_1 stores at site $S_{1.}$
  Let r_2 be a relation with schema R_2 stores at site $S_{2.}$
- Evaluate the expression $r_1 \bowtie r_2$ and obtain the result at S_1.
- **Motivation**: Shipping whole r_1 or r_2 can be very expensive!

1. Compute $temp_1 \leftarrow \Pi_{R_1 \cap R_2}(r_1)$ at S_1.
2. Ship $temp_1$ from S_1 to S_2.
3. Compute $temp_2 \leftarrow r_2 \bowtie temp_1$ at S_2
4. Ship $temp_2$ from S_2 to S_1.
5. Compute $r_1 \bowtie temp_2$ at S_1. This is the same as $r_1 \bowtie r_2$.

Illustration of Semijoin Strategy

- Say we need $r_1 \bowtie r_2$ at site S_1.
- **Perforance gain**: the total size of $temp_1$ and $temp_2$ is much smaller than that of r_1 or r_2.

$temp_1$ contains only the common attribute values. They decide the join result.



$r_1 \bowtie temp_2 = r_1 \bowtie r_2$ ☺

$temp_2$
$= r_2 \bowtie temp_1$
$= r_2 \bowtie \Pi_{R_1 \cap R_2}(r_1)$
$= \Pi_{R_2}(r_2 \bowtie r_1)$
$= r_2 \ltimes r_1$
I.e., those r_2 tuples that contribute to the join.

Formal Definition of Semijoin

- The **semijoin** of r_i with r_j is denoted by:
  - $r_i \ltimes r_j = \prod_{R_i} (r_i \bowtie r_j)$, where R_i is r_i's schema.
  - Thus, $r_i \ltimes r_j$ selects only those tuples of r_i that contribute to $r_i \bowtie r_j$.
- In step 3 on the previous slide
  - $temp_2 = r_2 \bowtie temp_1 = r_2 \bowtie \prod_{R_1 \cap R_2} (r_1) = \prod_{R_2} (r_2 \bowtie r_1) = r_2 \ltimes r_1$
  - That's why this strategy gets its name
- If we need $r_1 \bowtie r_2$ at site S_2, then we need to initiate the whole process at S_2 *s.t.* it will receive $r_1 \ltimes r_2$.
- For joins of several relations, the strategy can be extended to a series of semijoin steps.

Distributed Join Example: Naïve Strategies

- Consider the following setting and statistics:
- r_1 with schema R(A, B) at site S_1
  card(R) = 10,000
- r_2 with schema S(B, C) at site S_2
  card(S) = 50,000
- Attribute data value size:
  - A: 116 bytes; B: 4 bytes; C: 76 bytes.
- Basic costs:
  - c_0: initial set-up cost between any two sites = 10
  - c_1: transmission cost per data unit between any two sites = 1 per 1000 bytes
- Two naïve strategies and their costs
  - Join at S_1: Cost = 10 + (76+4)*50000/1000 = 4010 (shipping r_2 to S_1)
  - Join at S_2: Cost = 10 + (116+4)*10000/1000 = 1210 (shipping r_1 to S_2)

Shipping the smaller relation ☺

Distributed Join Example: Semijoin Strategy

Consider the following setting and statistics:

- r_1 with schema R(A, B) at site S_1
  card(R) = 10,000
- 1 card($\prod_B(r_1)$) = 2,000
  - #of distinct values on the join attribute
- 2 card($r_1 \ltimes r_2$) = 2,500
  - #of r_1 tuples that contribute to the join

- r_2 with schema S(B, C) at site S_2
  card(S) = 50,000
- 1 card($\prod_B(r_2)$) = 5,000
  - #of distinct values on the join attribute
- 2 card($r_2 \ltimes r_1$) = 5,000
  - #of r_2 tuples that contribute to the join

Semijoin cardinality

- Attribute data value size:
  - A: 116 bytes; B: 4 bytes; C: 76 bytes.
- Basic costs:
  - c_0: initial set-up cost between any two sites = 10
  - c_1: transmission cost per data unit between any two sites = 1 per 1000 bytes
- Semijion strategy costs
  - **Result at S_1**: Cost = 10 + 4*2000/1000 + 10 + (76+4)*5000/1000 = 428
  - **Result at S_2**: Cost = 10 + 4*5000/1000 + 10 + (116+4)*2500/1000 = 340

Agenda

- Introduction
- Distributed Data Storage
- Distributed Query Processing and Optimization
- Distributed Transactions

Distributed Transactions

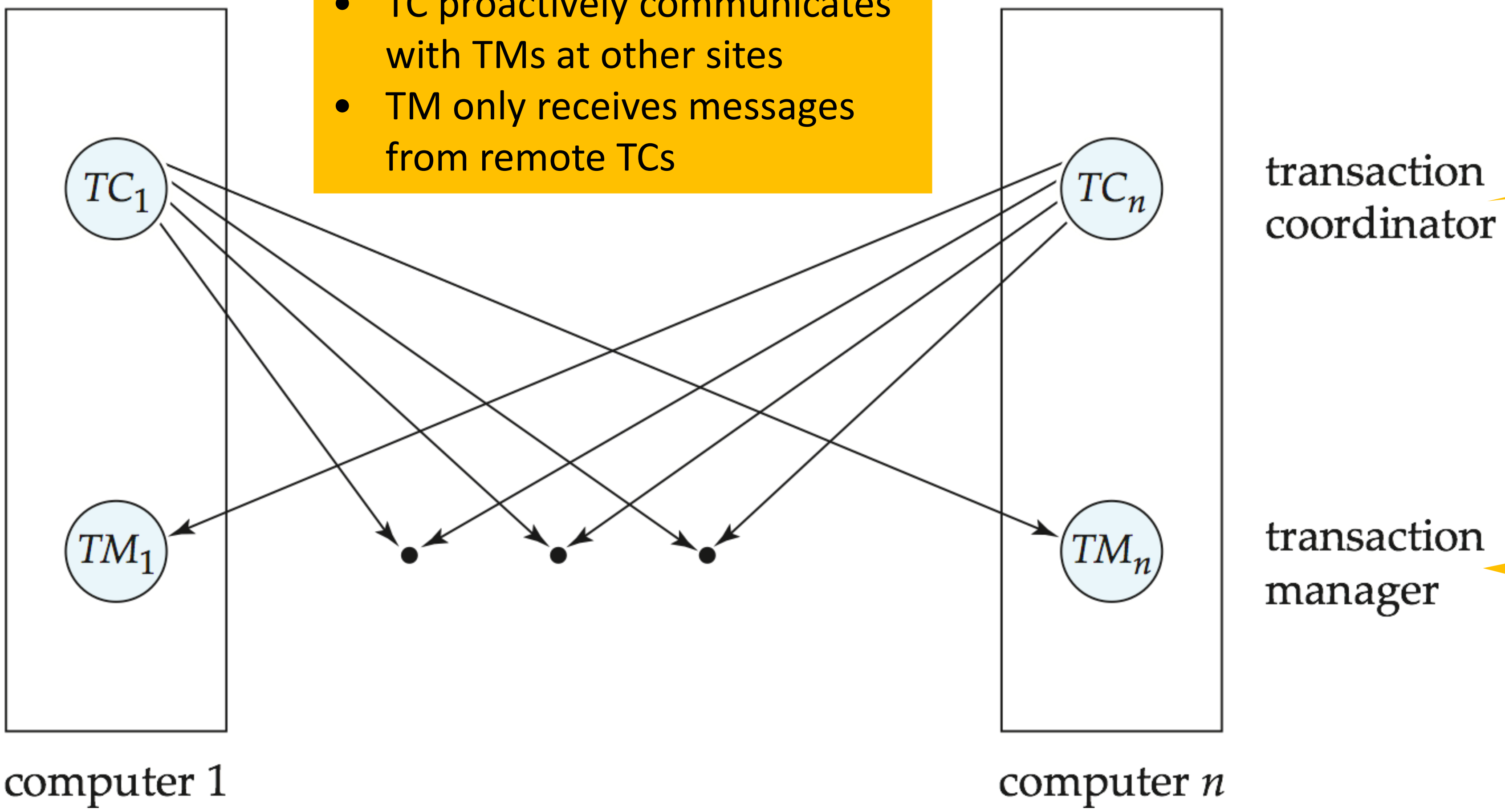
Transaction Manager
- Local role
- Used in centralized DBS

- Transaction may access data at several sites.
- Each site has a local **transaction manager** that is responsible for:
  - *Maintaining* a log for recovery purposes.
  - *Participating* in coordinating the concurrent execution of the transactions executing *at that site*.
- Each site has a **transaction coordinator** that is responsible for:
  - *Starting* the execution of a transaction that originates at the site.
  - *Breaking* the transaction to a number of subtransactions.
  - *Distributing* the subtransactions to the appropriate sites for execution.
  - *Coordinating* the termination of the transaction, which may result in the transaction being committed at all sites or aborted at all sites.

Transaction Coordinator
- Global role
- Not used in centralized DBS

Distributed Transaction System Architecture

- TC proactively communicates with TMs at other sites
- TM only receives messages from remote TCs



'Inter-site' coordinator

- Starts a transaction
- Breaks it into subtransactions
- Distributes them to other sites
- Coordinate among participating sites

***Local* manager**

- Maintains a log
- Participates in transactions coordinated by other sites

System Failures

- Failures unique to distributed systems:
  - Failure of a site.
  - Loss of messages
    - Handled by network transmission control protocols such as TCP/IP
  - Failure of a communication link
    - Handled by network protocols, by routing messages via alternative links
  - Network partition
    - A network is said to be partitioned when it has been split into two or more subsystems that lack any connection between them
      - Note: a subsystem may consist of a single node
- Network partitioning and site failures are generally *indistinguishable*.

Commit Protocols

- Commit protocols are used to ensure *atomicity* across sites
  - A transaction which executes at multiple sites must either be *committed at all* the sites or *aborted at all* the sites.
  - It's unacceptable to have a transaction committed at one site and aborted at another.
  - Consider the cross-site money transfer example again.
- The **two-phase commit** (2PC) protocol is widely used.

Two-Phase Commit Protocol (2PC)

- Assumes **fail-stop** model
  - Failed sites simply stop working, and do not cause any other harm, such as sending incorrect messages to other sites.
- Execution of the protocol is initiated by the **Transaction Coordinator** after the *last step* of the transaction has been reached.
- The protocol involves all the sites at which the transaction is executed.
  - All participants
- Let T be a transaction initiated at site S_i, and let the transaction coordinator at S_i be TC_i

Phase 1: Obtaining a Decision

- Coordinator asks all participants to *prepare* to commit transaction T.
  - TC_i adds the entry <**prepare** T> to the log and forces log to stable storage.
  - TC_i sends **prepare** T messages to all participants.
- Upon receiving the message, the Transaction Manager at a site determines if it can commit the transaction.
  - If not, add an entry <**no** T> to the log and send **abort** T message to TC_i
  - If the transaction can be committed, then:
    - Adds the entry <**ready** T> to the log
    - Forces *all entries* for T to stable storage
    - Send **ready** T message to TC_i

Phase 2: Recording the Decision

- *T* can be committed if TC_i receives a **ready** *T* message from *all* the participating sites; otherwise, *T* must be aborted.
  - If no message from a participant, then also failure/abort.
- Coordinator adds a decision entry, <**commit** *T*> or <**abort** *T*>, to the log and forces the entry onto stable storage. Once the entry reaches stable storage it is irrevocable (even if failures occur).
- Coordinator sends a message to each participant, informing it of the decision (commit or abort).
- Each participant takes the appropriate action locally.

2PC is able to handle different types of failures.

Illustration of Obtaining a Decision

'Inter-site' coordinator

1. <**prepare T**> to its local log
2. Message **prepare T** to each participant

Local manager

- Can I commit T locally?
- Yes: 1. <**ready T**> to the local log
  2. All T's entries to stable storage
  3. **Ready T** to TC_i
- No: 1. <**No T**> to the local log
  2. **Abort T** to TC_i

Decision

- **Commit T** if **Ready T** from all
- Otherwise, **Abort T**
  - No message from a participant => failure/abort

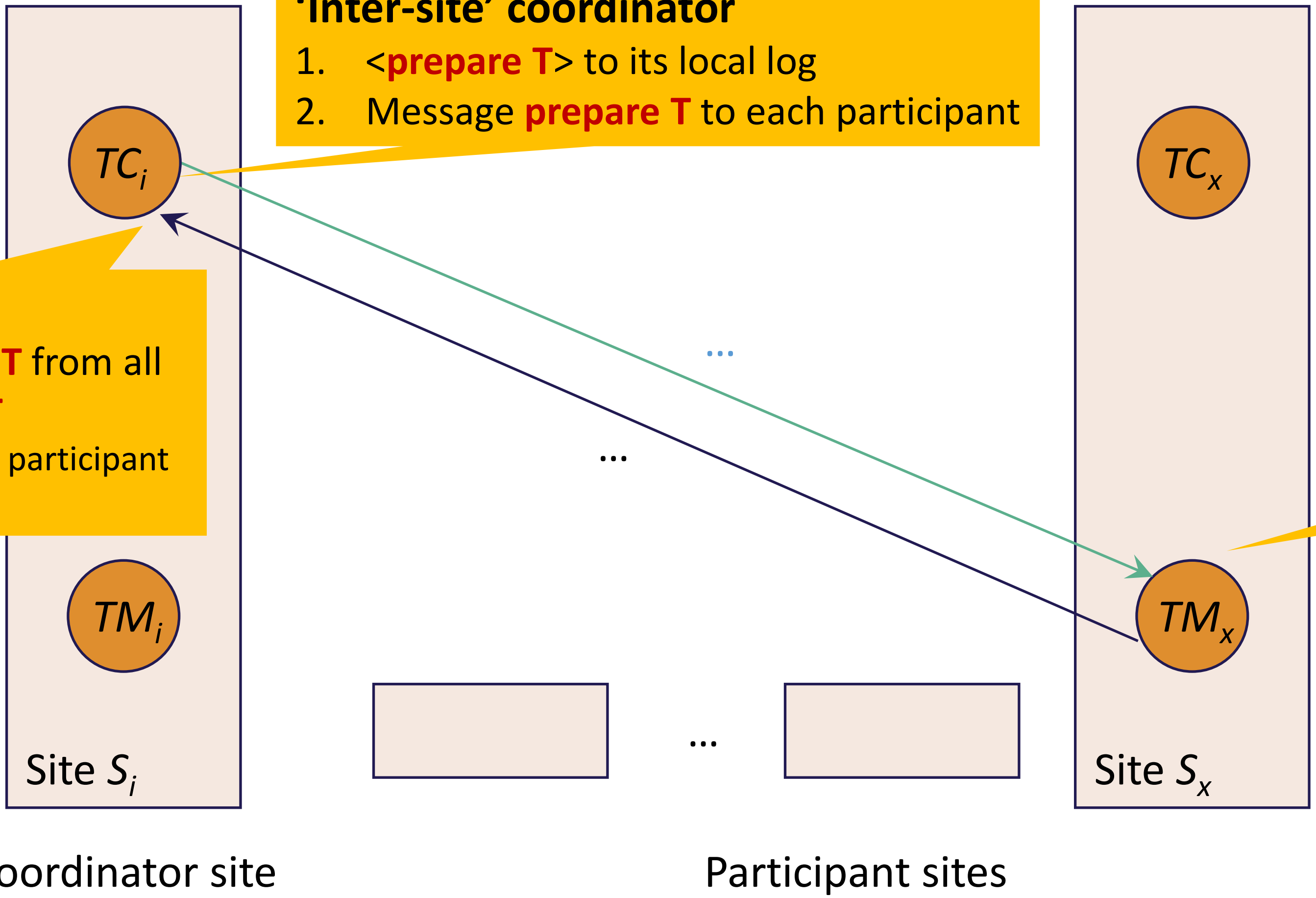
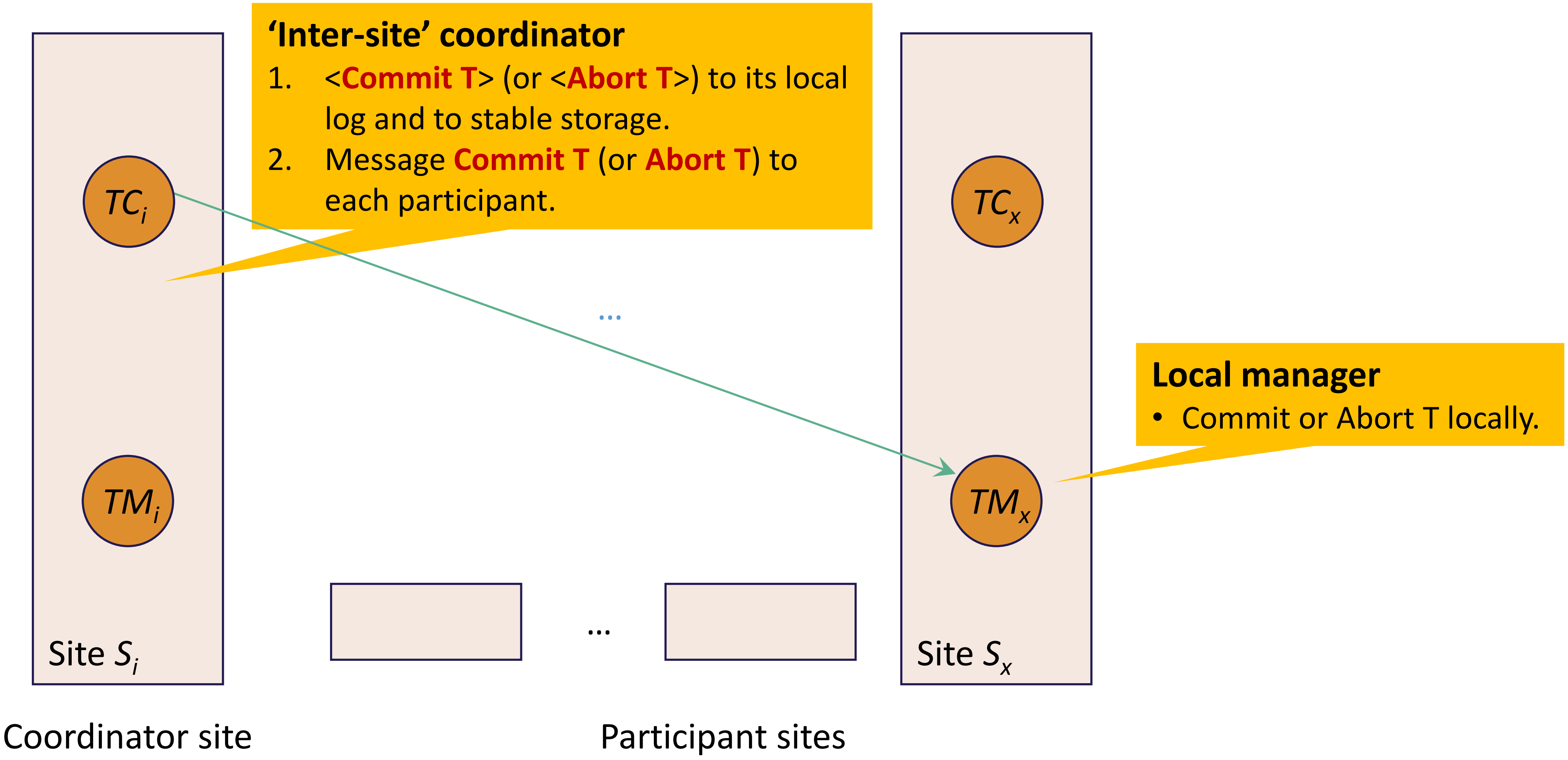


Illustration of Recording The Decision



Handling of Participant Failure

- When site S_x recovers, it examines its log to determine the fate of transactions active at the time of the failure.
  - Log contain <**commit** *T*> entry: site executes **redo** (*T*)
  - Log contains <**abort** *T*> entry: site executes **undo** (*T*)
  - Log contains <**ready** *T*> entry: site must consult TC_i to determine the fate of *T*.
    - If *T* committed, **redo** (*T*)
    - If *T* aborted, **undo** (*T*)

- If the log contains no control entries concerning *T*, S_x got failed before responding to the **prepare** *T* message from TC_i
  - Since the failure of S_x precludes the sending of such a response, C_i must abort *T*
  - S_x must execute **undo** (*T*)

Handling of Coordinator Failure

- If a coordinator fails while the commit protocol for *T* is executing, then participating sites must decide on *T*'s fate:
  - If an active site contains a <**commit** *T*> record in its log, then *T* must be committed.
  - If an active site contains an <**abort** *T*> record in its log, then *T* must be aborted.
  - If some active participating site does not contain a <**ready** *T*> record in its log, then the failed coordinator TC_i cannot have decided to commit *T*. Can therefore abort *T*.
  - If none of the above cases holds, then all active sites must have a <**ready** *T*> record in their logs, but no additional control records (such as <**abort** *T*> of <**commit** *T*>). In this case active sites must wait for TC_i to recover, to find decision.
- **Blocking problem**: active sites may have to wait for failed coordinator to recover.

Handling of Network Partition

- If the coordinator and all its participants remain in one partition, the failure has no effect on the commit protocol.
- If the coordinator and its participants belong to several partitions:
  - Sites that are not in the coordinator’s partition think the coordinator has failed and execute the protocol to deal with failure of the coordinator.
    - No harm results, but sites may still have to wait for decision from coordinator.
  - The coordinator and the sites in the same partition think that the sites in the other partition(s) have failed and follow the usual commit protocol.
    - Again, no harm results

Summary

- Distributed Data Storage
  - Replication and fragmentation
- Distributed Query Processing
  - Cost measure
  - Query tree transformation in the presence of fragments
  - Join strategies, semijoin
- Distributed Transactions
  - Two phase commit protocol

Readings

- Mandatory readings (for both Lectures 2 and 3)
  - A. Silberschatz, H. F. Korth, S. Sudarshan: Database System Concepts (7th edition), McGraw-Hill. Chapters 20, 21, 22 and 23
    - Optional: 21.3, 21.5, 22.6, 22.7, 22.8, 23.4, 23.5, 23.6, 23.7, 23.8

Exercise 1

Consider the following setting and statistics

- r_1 with schema R(A, B) at site S_1
  card(R) = 10,000
- card($\prod_A(r_1)$) = 1,000
  card($\prod_B(r_1)$) = 2,000
- card($r_1 \ltimes r_2$) = 1,500

- r_2 with schema S(A, C) at site S_2
  card(S) = 50,000
- card($\prod_A(r_2)$) = 3,000
  card($\prod_C(r_2)$) = 5,000
- card($r_2 \ltimes r_1$) = 3,500

- Attribute data value size:
  - A: 10 bytes; B: 20 bytes; C: 30 bytes.
- Basic costs:
  - c_0: initial set-up cost between any two sites = 20
  - c_1: transmission cost per data unit between any two sites = 1 per 500 bytes
- **Questions**: If we use the semijoin strategy to obtain $r_1 \bowtie r_2$,
  - What is the total cost to obtain the result at S_1?
  - What is the total cost to obtain the result at S_2?

Exercise 2

Site 1: **EMPLOYEE**

- Schema: (EID, Name, Salary, DID)
  - EID: 10 bytes
  - Name: 20 bytes
  - Salary: 20 bytes
  - DID: 10 bytes
  - Totally 1000 tuples

Site 2: **DEPARTMENT**

- Schema: (DID, DName)
  - DID: 10 types
  - Dname: 20 types
  - Totally 50 tuples

- **Question**: Site 3 needs to find the name of employees and their department names. Figure out at least 3 strategies for this distributed join query and calculate the total amount of data transfer for each strategy.