Ordering Messages in Distributed Virtual Environments

Richard M. Fujimoto
Professor

Computational Science and Engineering Division
College of Computing
Georgia Institute of Technology
Atlanta, GA 30332-0765, USA

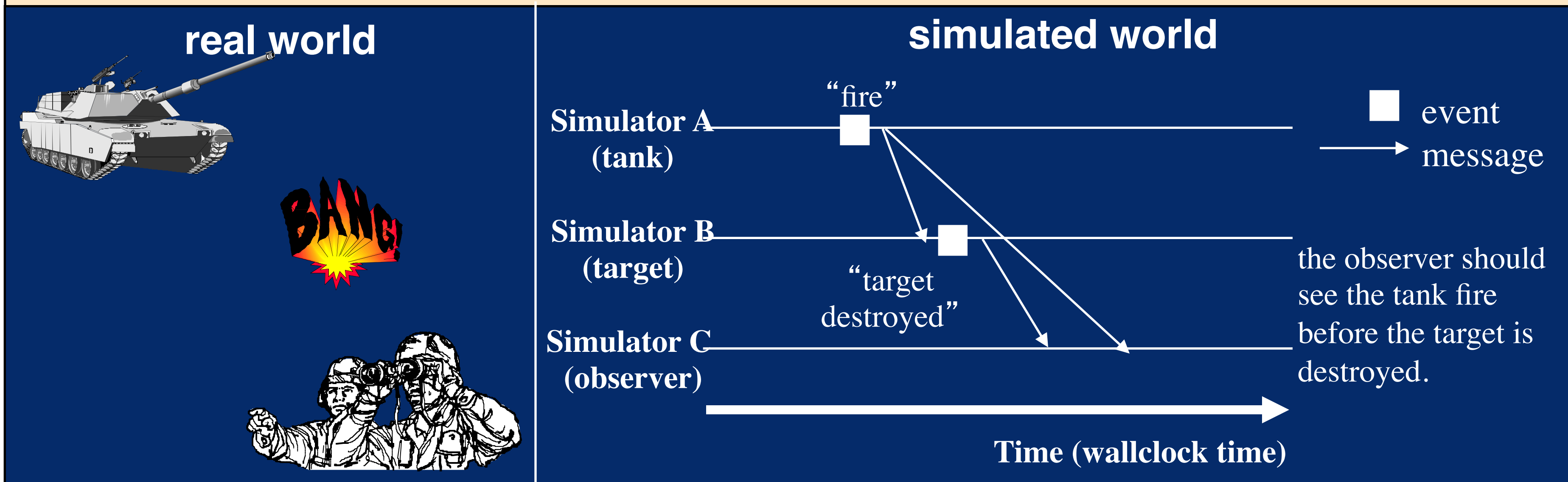
http://www.cc.gatech.edu/~fujimoto/

Outline

- Causal Message Ordering
  - Happens before relationship
  - Causal order message delivery
- Causal Order Implementation
  - Central message dispatcher
  - Barriers
  - Vector time stamps
- Limitations

Event Order

- “Things” happen in the real world in a certain order (e.g., cause & effect).
- It should appear that events in the simulated world happen in the same order as the real world actions that they represent.



The observer could “see” the target is destroyed before the tank fired upon it!

Temporal anomalies such as this may or may not be acceptable, depending on the federation’s goals

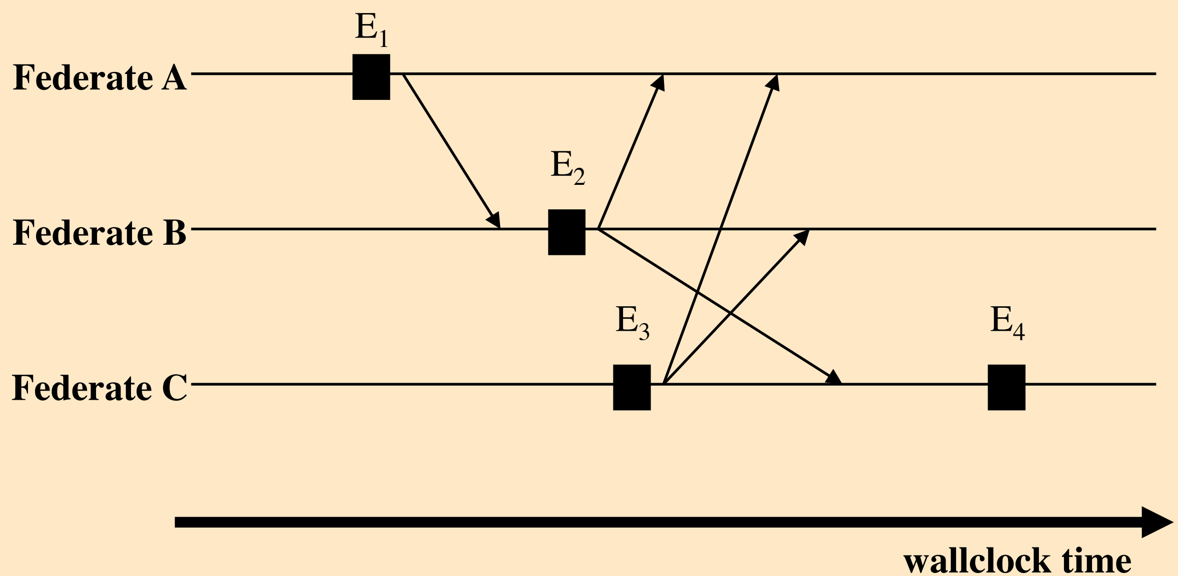
Correct ordering of events can be achieved by assigning a time stamp (logical time) to each event, and ensuring events are delivered in time stamp order (e.g., using conservative or optimistic synchronization)

This may entail significant computation/communication overheads

Causal Order

- Defined for distributed computing in general (not just simulation)
- Assumptions
  - Set of processes; message-based communication
  - Each process's execution a sequence of actions
    - Local computation (event)
    - Send message
    - Deliver message to process
- Causal order defines an ordering among actions/ messages

The "Happens Before" Relationship



$E_1 \rightarrow E_4$

$E_1 \not\rightarrow E_3$

Definition (Lamport `78) "happens before" relationship (->):

Consider two actions (event, send, or deliver), A_1 and A_2

- if A_1 & A_2 occur in the same process and A_1 precedes A_2, then A_1 -> A_2
- if A_1 is a send, and A_2 is a delivery of the same message, then A_1 -> A_2
- if A_1 -> A_2 and A_2 -> A_3, then A_1 -> A_3 (transitivity)

Actions that are not causally related are said to be **concurrent**

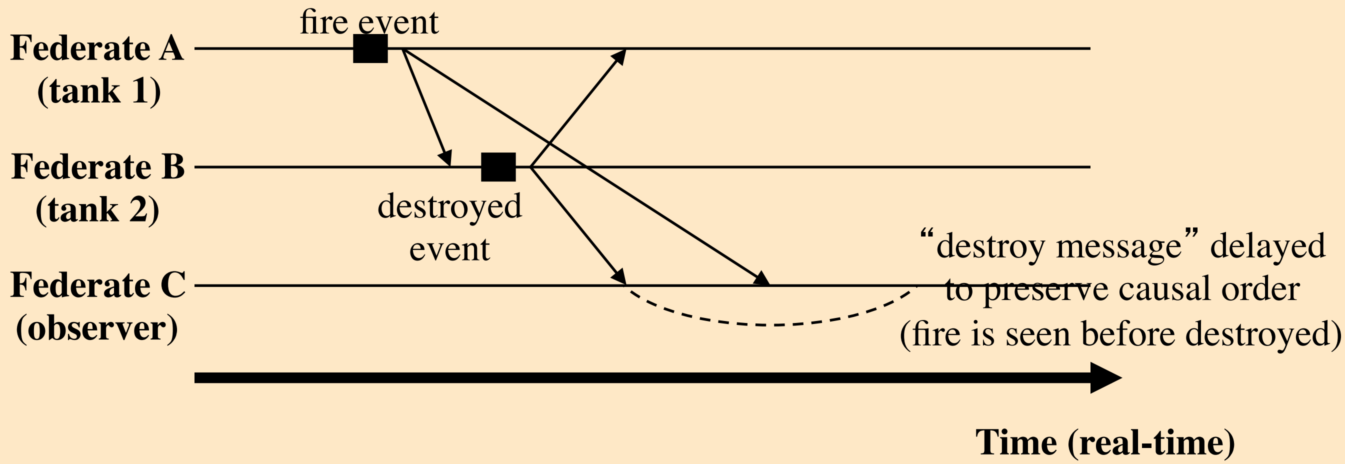
Basic idea: If there is a left-to-right path from A_1 to A_2, then A_1 -> A_2

Causal Order Message Delivery

A message delivery service is said to be **causally ordered** if for any two messages M_1 and M_2 sent to the same federate where M_1 and M_2 contain notices for events E_1 and E_2, respectively, and E_1 -> E_2,

then M_1 is delivered to the federate before M_2

Messages for concurrent events may be delivered in any order



Observation: Causal order message delivery avoids certain anomalies that might occur in receive order delivery

Causally order does not consider application semantics - may impose an ordering on independent events

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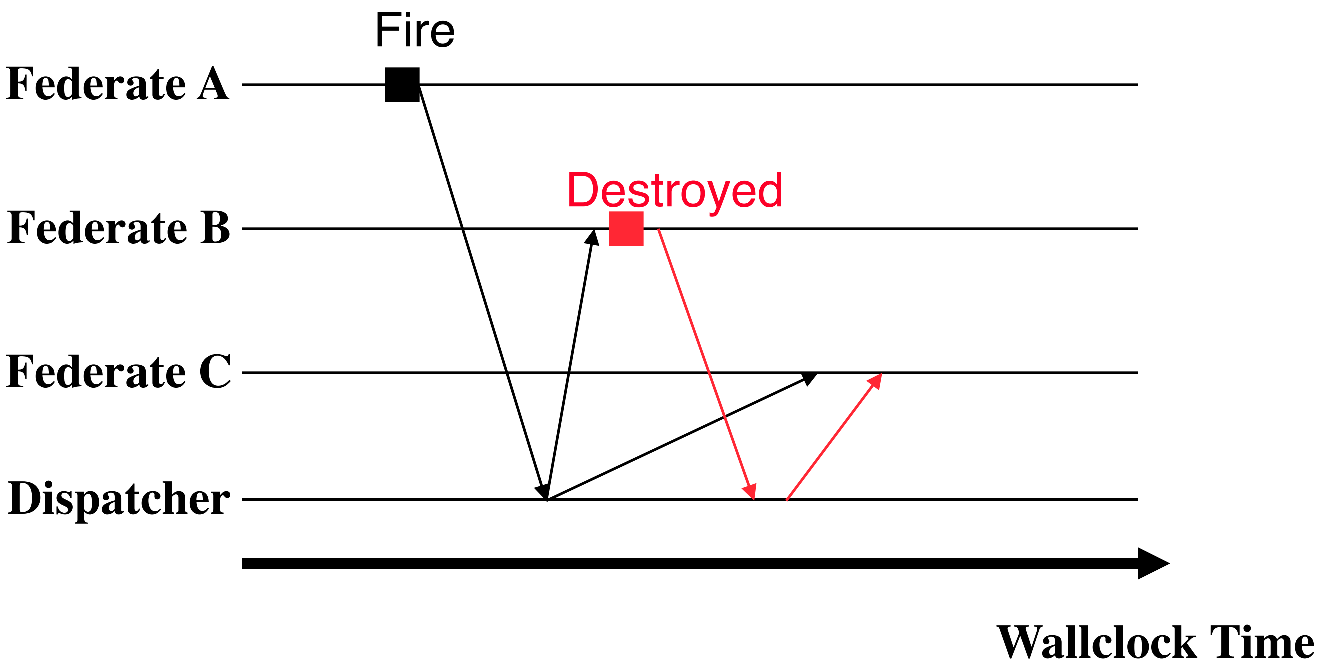
Central Dispatcher Implementation

- Assume reliable and ordered communication (e.g., TCP)
- Route all communications through a central message dispatcher (within the RTI) that forwards message to its destination



Any event that depends on Fire event must be sent by the dispatcher after it sends all messages for the Fire event, ensuring causal order delivery

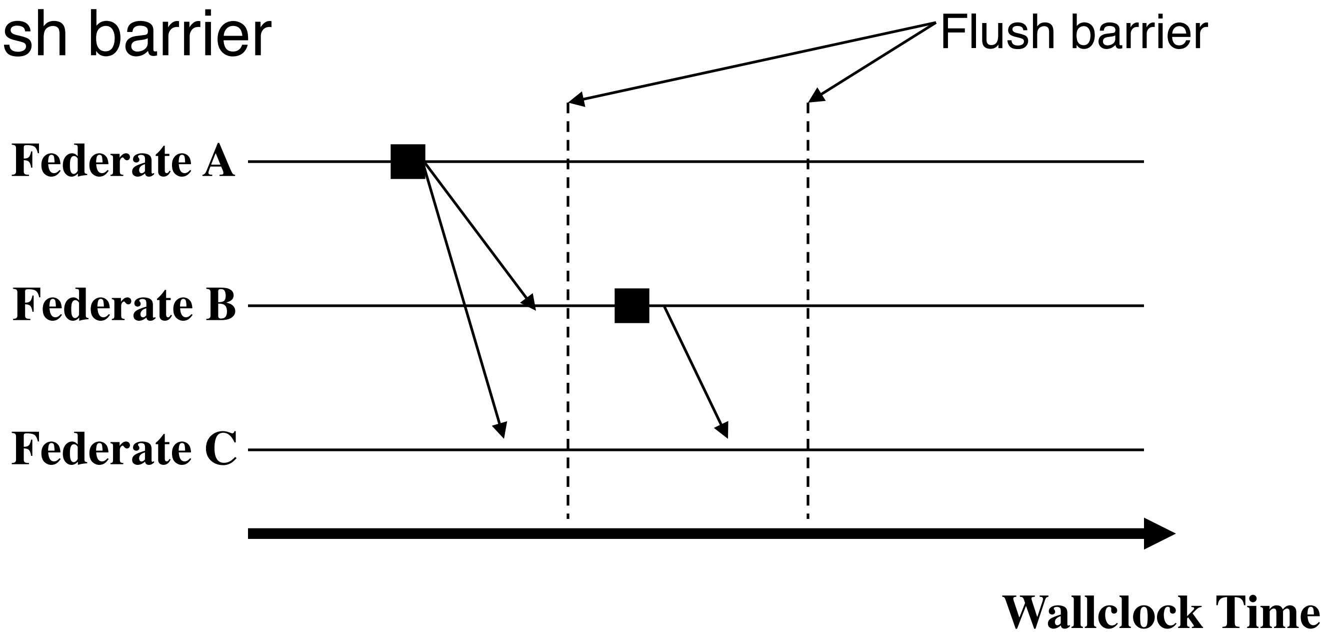
Implementation Using Barriers

Assume reliable, ordered message delivery

Main loop in each simulator:

While (not done with simulation)

- Deliver all events from RTI
- Barrier
- Process events, send messages
- Flush barrier

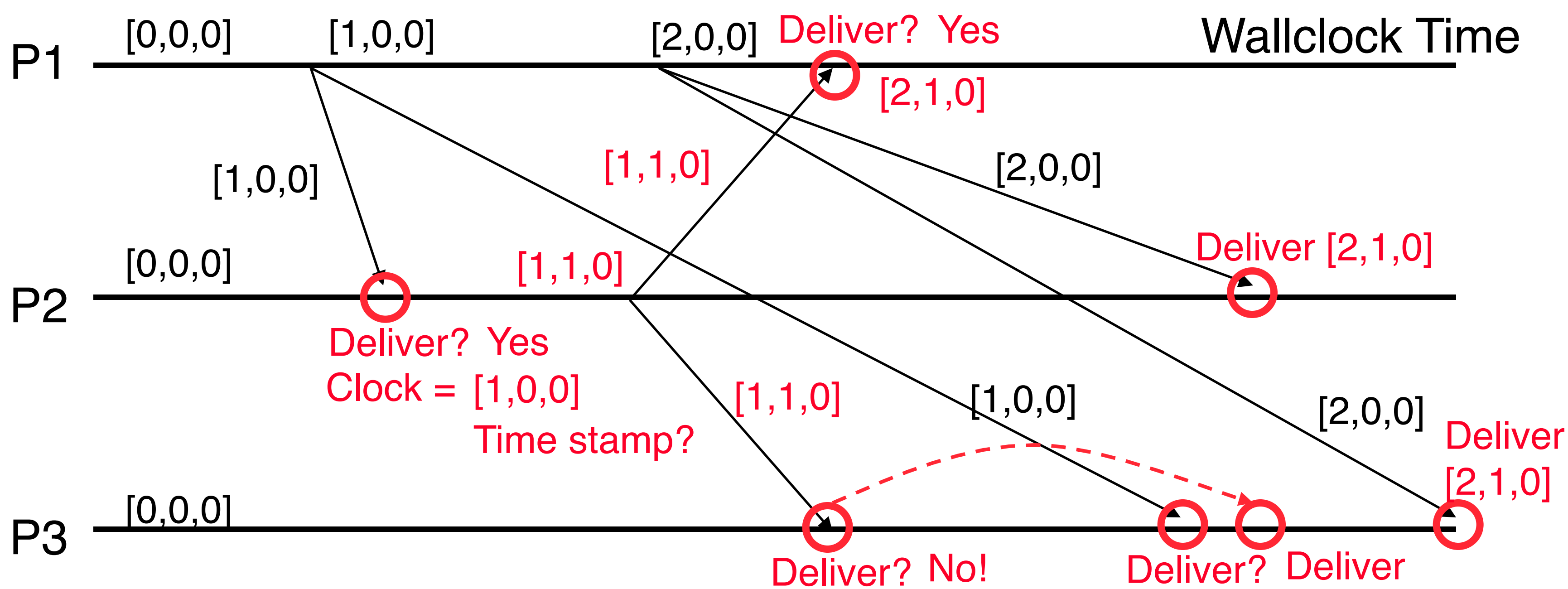


Barrier serializes causally related events in different processors

Vector Clocks

- Applicable to closed multicast group (sender is also a member of the group)
- Process i maintains vector clock C_i:
  - $C_i[i]$ = number of messages process i has sent to group
  - $C_i[j]$ ($j \neq i$) = number of messages sent to group by process j that have been delivered to process i (number of messages from j causally preceding process i's current event)
  - Example: $C_1 = (1, 2, 3, 4)$
    - Process 1 has sent 1 message
    - Process 1 has delivered 2 messages from process 2, 3 messages from process 3, and 4 messages from process 4
- Attach a vector time stamp to each message; when process i sends a message:
  - Increment $C_i[i]$
  - Use process i's vector clock as message time stamp
  - Indicates which messages causally precede this message

Message Delivery



Rules for message delivery

- A message M with time stamp T[ ] is sent by process S to process R
- This message can be delivered to R when
  - T[S] = C_R[S] + 1, and /* check this is the next message from S */
  - T[j] ≤ C_R[j], all j ≠ S, /* messages preceding M already delivered */
  - /* If T[j] < C_R[j], R has received other messages from process j */

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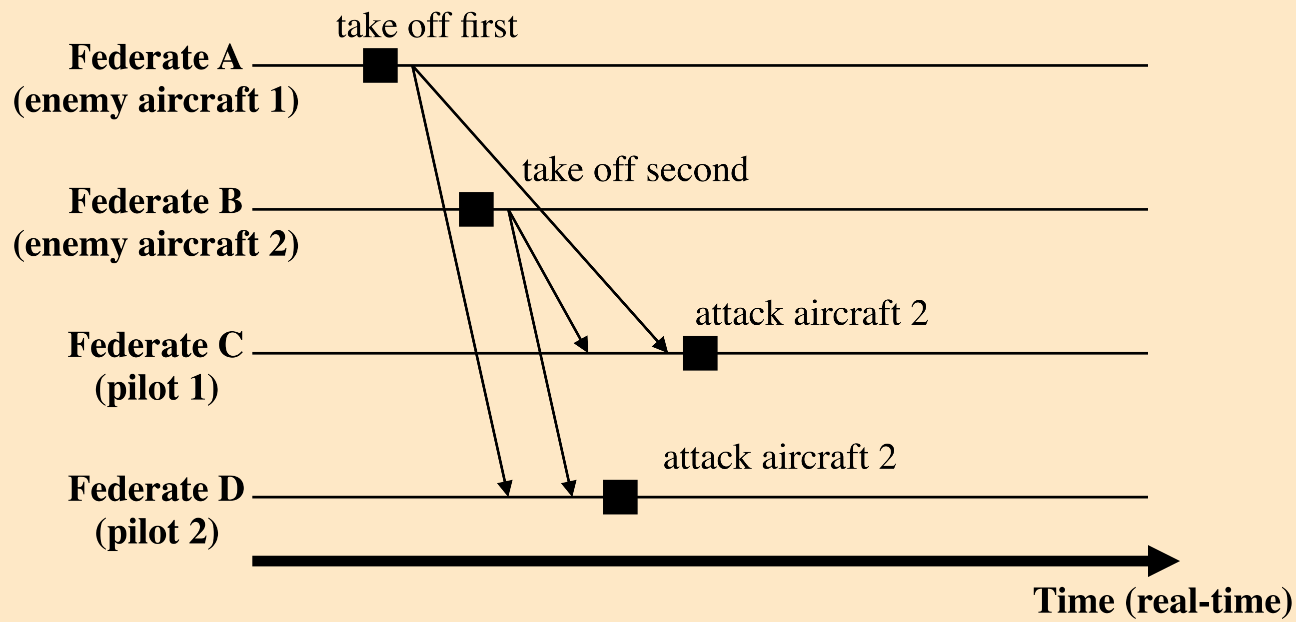
Causal and Totally Ordered

Observation: causal order allows different federates to receive messages for concurrent events in different orders

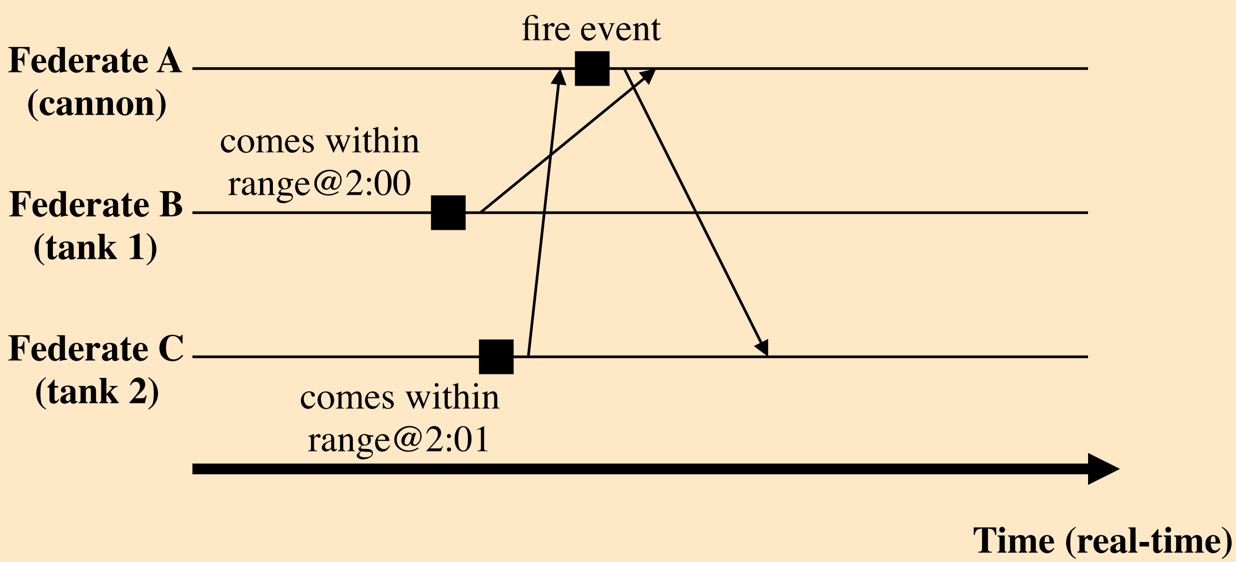


- pilot 1 has orders to attack the first enemy aircraft to take off; pilot 2 has orders to attack the second
- both pilots attack enemy aircraft #2

Causal and totally ordered: all federates receiving messages for the same events receive them in the same order.

Causal/Total Order: Limitations

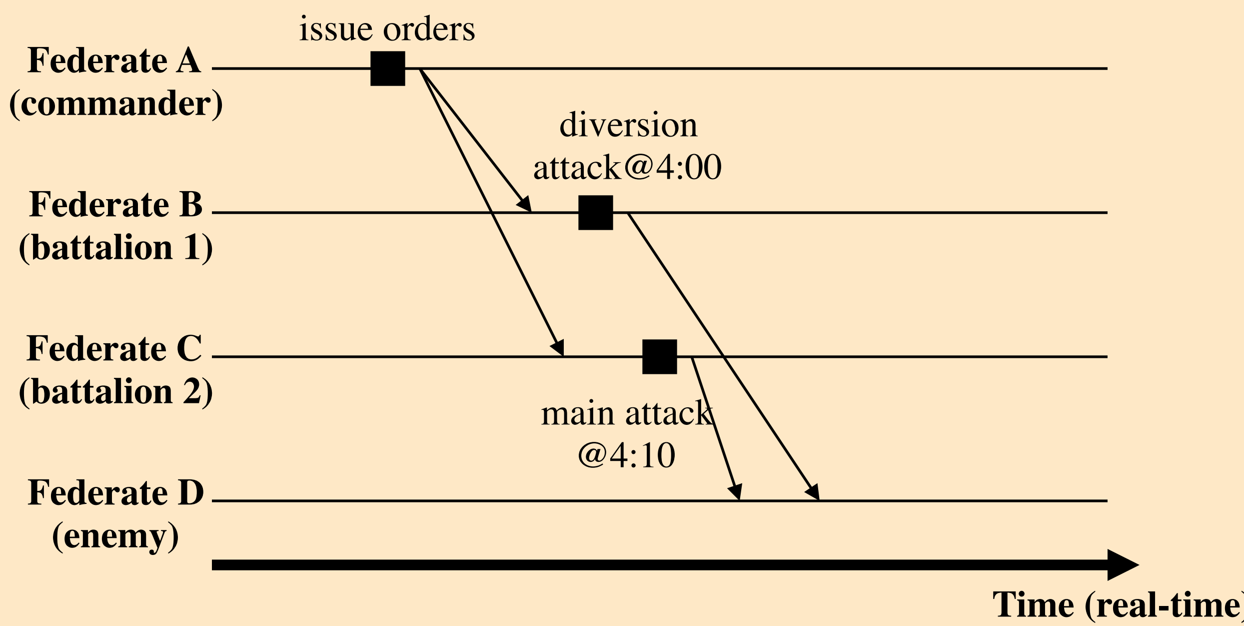
Even with total ordering, no ordering guarantees for concurrent events



- Federate A has orders to fire upon first target to come with range
- Federate B comes into range first, then Federate C comes into range
- "Come into range" events are concurrent; causal order does not guarantee any order of delivery
- Federate C's message is delivered to Federate A first; C is incorrectly fired upon.
- Timestamp order ensures proper order of delivery

Causal/Total Order: Limitations

Hidden dependencies: dependencies between events that are not conveyed explicitly via messages may not be preserved.



- Federate A issues orders for operation (diversion, then main attack)
- Federate B begins diversion attack
- Federate C begins main attack
- Messages from B and C are not causally related; enemy federate may observe the main attack before the diversion!
- timestamp order guarantees proper order of delivery

Summary

- Receive order is commonly used in virtual environments, but can lead to anomalies
- Time stamp order solves problem, but at cost of relatively high overheads
- Causal order provides an alternate solution
  - Based on Lamport's happens-before relationship
  - Relatively simple implementations (central dispatcher, vector time stamps) available
  - Does not eliminate all temporal anomalies
- Total ordering eliminates more, but not all anomalies