CSCI 4210/6210
Parallel & Distributed Simulation

PDES: Time Warp Mechanism

Distributed Snapshots and Fossil Collection

Global Virtual Time

*Wallclock time T (GVT_t) during the execution of a Time Warp simulation is defined as the **minimum** time stamp among all unprocessed and partially processed messages and anti-messages in the system at wall-clock T.*

Outline

- **Consistent Cuts**
  - » Cut points
  - » Cut messages
  - » Cut values
- **Mattern's GVT Algorithm**
  - » Colors
  - » Vector counters
  - » Pipelined algorithm
- **Fossil Collection**
- **Thursday: We will do an additional example using Mattern's Algorithms to determine GVT.**

Review: Samadi's Algorithm

- **Transient message problem:**
  - » **Solution: Message acknowledgements**
- **Simultaneous message problem:**
  - » **Solution: Mark acknowledgements sent after reporting local minimum**
  - » **Caveat: Just message acks are not enough (marked message acks are needed).**
- **Overhead:**
  - » **Message acknowledgments:**
    - – **Message acknowledgment for**
      - **each message and**
      - **anti-message.**

Mattern's Algorithm

- **Asynchronous**
  - » **Executes in background concurrent with time warp execution (does not require the simulation to "freeze" (i.e., block the LPs).**
- **Avoids message acknowledgements**
- **Approach: Based on techniques for creating distributed snapshots (consistent cut)**
  - » **We will see what it means to be a consistent cut**

» **Can some asynchronous algorithms compute *exact* GVT(t)?**

» **What about synchronous algorithms?**

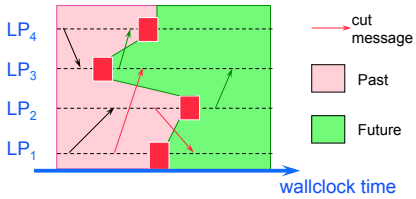
Consistent Cuts

Cut point:

Cut:

Cut message:

Consistent cut:



Cut value:

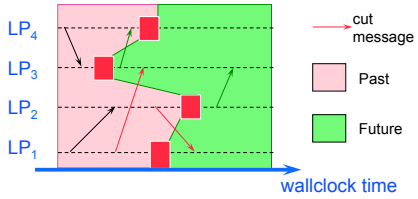
Consistent Cuts

Cut point: an instant dividing computation into **past** and **future**

Cut:

Cut message:

Consistent cut:



Cut value:

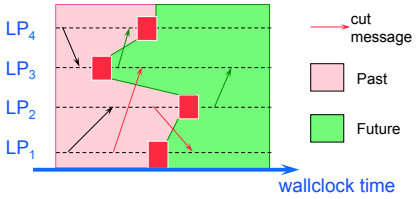
Consistent Cuts

Cut point: an instant dividing computation into **past** and **future**

Cut: set of cut points, one per processor

Cut message:

Consistent cut:



Cut value:

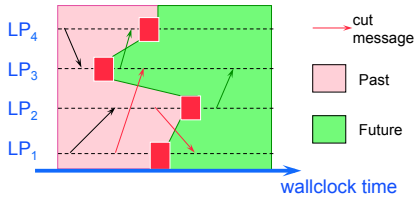
Consistent Cuts

Cut point: an instant dividing computation into **past** and **future**

Cut: set of cut points, one per processor

Cut message: a message that was sent in the past, and received in the future

Consistent cut:



Cut value:

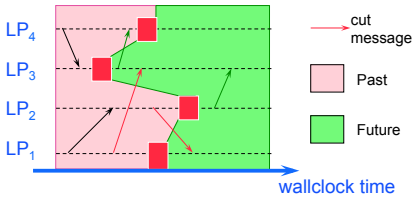
Consistent Cuts

Cut point: an instant dividing computation into **past** and **future**

Cut: set of cut points, one per processor

Cut message: a message that was sent in the past, and received in the future

Consistent cut: a cut where all messages crossing the cut are cut messages



Cut value:

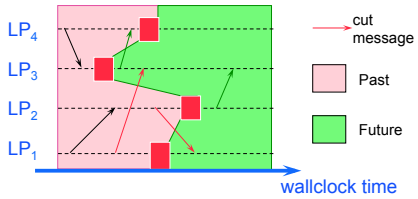
Consistent Cuts

Cut point: an instant dividing computation into **past** and **future**

Cut: set of cut points, one per processor

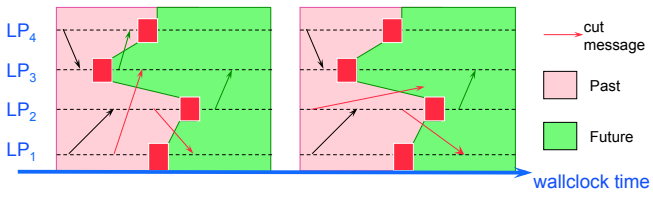
Cut message: a message that was sent in the past, and received in the future

Consistent cut: a cut where all messages crossing the cut are cut messages



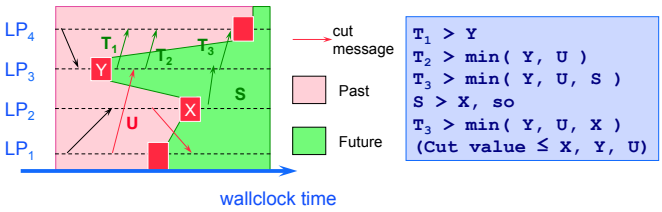
Cut value: minimum among (1) local minimum of each LP at its cut point and (2) time stamp of cut messages

Cuts: Divides Past and Future



- **Consistent Cuts: Includes local state at its cut-point & all its transient messages.**
- **Observation: Time stamp of a message sent after a cut point at wallclock time T must be at least as large as the minimum of:**
  - **the smallest time stamp of any unprocessed event in the processor at time T**
  - **the smallest time stamp of any message received by the processor after time T.**
- **GVT must be smaller than or equal to both of these quantities**

Observation 1



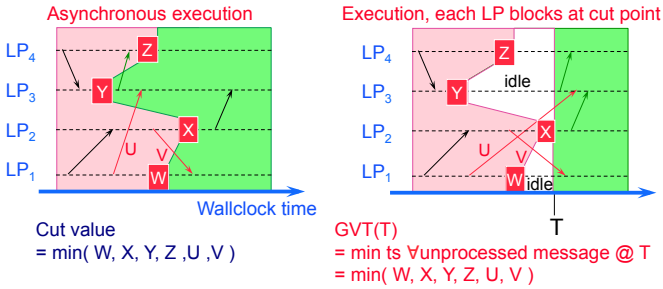
$T_1 > Y$
$T_2 > \min(Y, U)$
$T_3 > \min(Y, U, S)$
$S > X$, so
$T_3 > \min(Y, U, X)$
(Cut value $\leq X, Y, U$)

Any message crossing cut from future to past must have a time stamp > the cut value, so they can be ignored when computing the cut value

Message generated by an LP after its cut point must have time stamp greater than the minimum of

- **The LP's local minimum at its cut point**
- **The time stamp of messages received after the cut point**

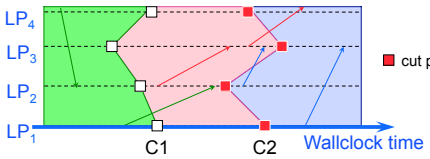
Observation 2



- Cut value equal to GVT(T) using **synchronous GVT** algorithm (freeze LPs: no new computations nor message sends/receives).
  - » Events generated after cut have time stamp > cut value
- **Cut value can be used as a GVT value**

Mattern's GVT Algorithm

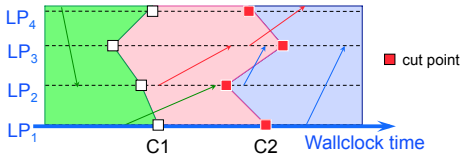
Challenge: accounting for cut messages



Approach:

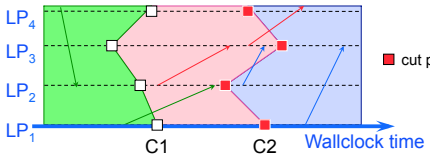
- Construct two cuts C1, C2, approximate cut value along C2
  - » Organize processes in ring, pass token around ring
- Ensure no message that crosses C1 also cross C2
  - » Color LPs, change LP color at each cut point
  - » Color (green/red) each message to that of LP sending message (message tag)
  - » Maintain send/receive message counters
- GVT = min(local min along C2, time stamp of red messages)

Algorithm Overview



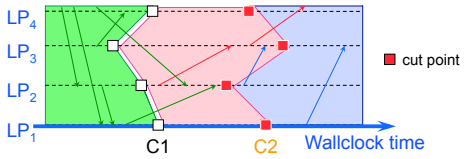
- *The first cut:*
  - » *Changes color of each process (green to red)*
  - » *Determine number of green messages sent to each process*
- *The second cut:*
  - » *Each process makes sure all green messages sent to it have been received before laying down a cut point*
  - » *Compute global minimum (GVT value)*

How does an LP know it has received all its green messages?



- LP_i maintains vector $V_i[1:N]$, where N = #LPs
  - » $V_i[i]$ = number of green messages received by LP_i
  - » $V_i[r]$ = number of green messages sent by LP_i to LP_r
- C2: LP_i cannot pass token until
  - » $V_i[i] = \sum V_s[i]$ (summed over all $s \neq i$)
- C1: Token includes vector to accumulate send counters

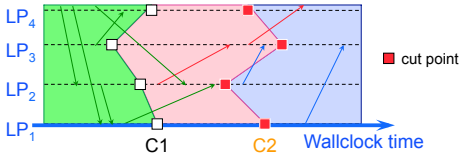
Example: Vector Counters



Vector counters for green messages (at C2) $i = j$ *received:*

V_1	V_2	V_3	V_4
$V_1[4] = 0$			

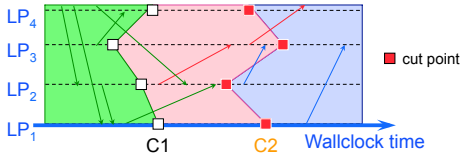
Example: Vector Counters



Vector counters for green messages (at C2) **`i = j`** *received:*

V_1	V_2	V_3	V_4
$V_1[4] = 0$			
$V_1[3] = 0$			

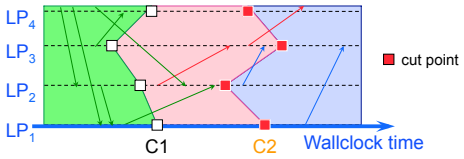
Example: Vector Counters



Vector counters for green messages (at C2) **`i = j`** *received:*

V_1	V_2	V_3	V_4
$V_1[4] = 0$			
$V_1[3] = 0$			
$V_1[2] = 1$			
.			

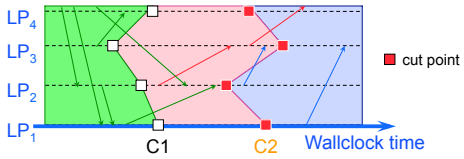
Example: Vector Counters



Vector counters for green messages (at C2) **`i = j`** *received:*

V_1	V_2	V_3	V_4
$V_1[4] = 0$			
$V_1[3] = 0$			
$V_1[2] = 1$			
$V_1[1] = -2$			

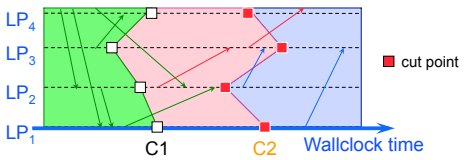
Example: Vector Counters



Vector counters for green messages (at C2) **`i = j`** *received:*

V_1	V_2	V_3	V_4
$V_1[4] = 0$	$V_2[4] = 0$		
$V_1[3] = 0$	$V_2[3] = 0$		
$V_1[2] = 1$	$V_2[2] = -3$		
$V_1[1] = -2$	$V_2[1] = 1$		

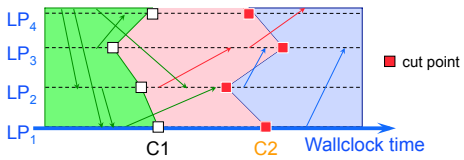
Example: Vector Counters



Vector counters for green messages (at C2) **`i = j`** *received:*

V_1	V_2	V_3	V_4
$V_1[4] = 0$	$V_2[4] = 0$	$V_3[4] = 1$	
$V_1[3] = 0$	$V_2[3] = 0$	$V_3[3] = 0$	
$V_1[2] = 1$	$V_2[2] = 3$	$V_3[2] = 0$	
$V_1[1] = -2$	$V_2[1] = 1$	$V_3[1] = 0$	

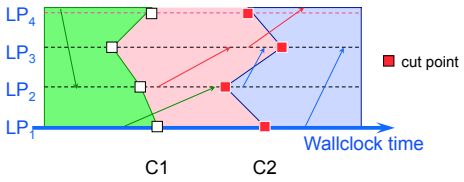
Example: Vector Counters



Vector counters for green messages (at C2) **`i = j`** *received:*

V_1	V_2	V_3	V_4
$V_1[4] = 0$	$V_2[4] = 0$	$V_3[4] = 1$	$V_4[4] = -1$
$V_1[3] = 0$	$V_2[3] = 0$	$V_3[3] = 0$	$V_4[3] = 0$
$V_1[2] = 1$	$V_2[2] = -3$	$V_3[2] = 0$	$V_4[2] = 2$
$V_1[1] = -2$	$V_2[1] = 1$	$V_3[1] = 0$	$V_4[1] = 1$

Mattern's GVT Algorithm



- **Local Variables (in each logical process LP_i):**
  - T_{red} = min time stamp among red messages sent by LP (even non-cut red messages!)
  - $V_i[1:N]$ = message send / receive counters
- **Token: CMsg**
  - $CMsg\_T_{min}$ = accumulator, smallest local minimum so far
  - $CMsg\_T_{red}$ = accumulator, smallest red message time stamp so far
  - CMsg_Count[1:N] = # messages sent to each LP

Mattern's GVT Algorithm

- Message send by green logical process from LP_i to LP_j
  - $V_i[j] = V_i[j] + 1$
- LP_i receives a green message
  - $V_i[i] = V_i[i] - 1$
- Control message, first cut:
  - Change color of process to red
  - $CMsg\_Count = CMsg\_Count + V_i$
  - Forward control message to next process in ring
- Message send with time stamp ts by a red LP
  - $T_{red} = min(T_{red}, ts)$
- Control message, second cut:
  - wait until $V_i[i] = CMsg\_Count[i]$ i.e., #received = #sent
  - $CMsg\_T_{min} = min(CMsg\_T_{min}, T_{min})$
  - $CMsg\_T_{red} = min(CMsg\_T_{red}, T_{red})$
  - forward token to next process in ring

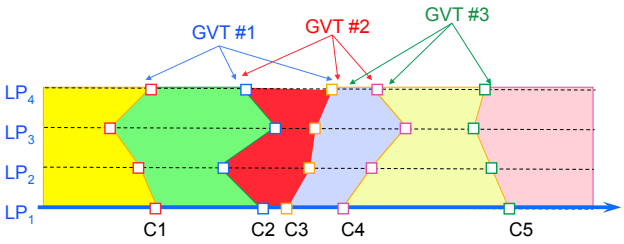
Fossil Collection

- **Batch fossil collection**
  - After GVT computation, scan through list of LPs mapped to processor to reclaim memory and commit I/O operations
  - May be time consuming if many LPs
- **On-the-fly Fossil Collection**
  - After processing event, place memory into "free memory" list
  - Before allocating memory, check that time stamp is less than GVT before reusing memory

Summary

- Consistent cuts
- Cut value can be used as an estimate of GVT
  - Local minimum at each LP
  - Cut messages
- Construct second consistent cut
  - Coloring LPs, messages
  - Vector counter to determine when an LP has received all relevant cut messages
- Pipeline GVT computation, continuously circulating token
- Numerous variations
  - Could implement cuts with other communication topologies, e.g., butterfly
  - Other ways to deal with transient messages, e.g., global count and abort/retry mechanism for second cut, etc.

Distributing GVT Values & Pipelining



Pipelined execution

- Overlap successive GVT computations: first GVT uses C1, C2, C3, second uses C2, C3, C4, etc.
- Each cut computes a new GVT value
- Continuously circulate GVT token