An example run of the Chandy-Lamport snapshot algorithm

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Introduction

A snapshot algorithm attempts to capture a coherent global state of a distributed system (for the purpose of debugging or checkpointing, for instance). This particular snapshot algorithm — the *first* one, as far as I know — was proposed by Mani Chandy and Leslie Lamport in their 1985 paper "Distributed Snapshots: Determining Global States of Distributed Systems". Lamport has a funny anecdote about the paper's origin:

The distributed snapshot algorithm described here came about when I visited Chandy, who was then at the University of Texas in Austin. He posed the problem to me over dinner, but we had both had too much wine to think about it right then. The next morning, in the shower, I came up with the solution. When I arrived at Chandy's office, he was waiting for me with the same solution.

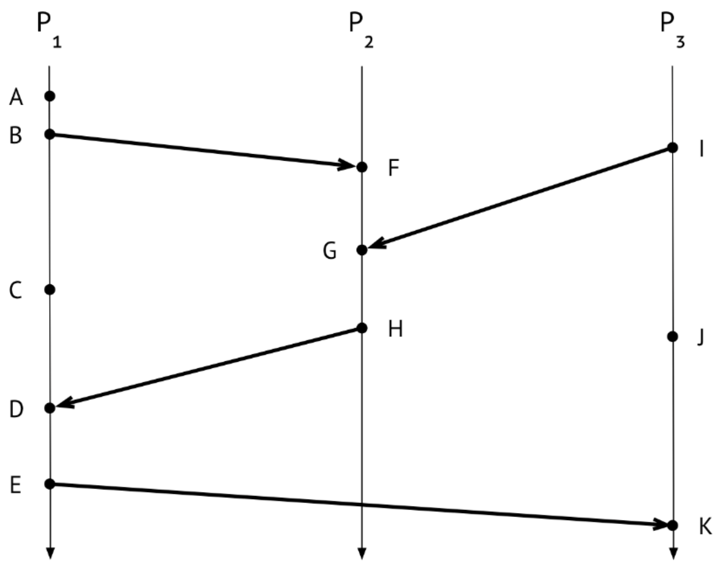
Getting to relate this anecdote to my class was at least half my motivation for wanting to cover the Chandy-Lamport algorithm in the first place.

Let's jump in. We're going to model the system we're snapshotting as a collection of processes that can send and receive messages among themselves. Sending and receiving are *events* that take place on processes; in this example, there also happen to be *internal* events that are neither sends nor receives. Messages are sent and received along *channels*, which are FIFO queues going between each pair of processes. It turns out to be important that the channels have FIFO behavior for the Chandy-Lamport algorithm to work.

We'll say that processes in our system are named P1, P2, etc., and that the channel from process Pi to process Pj is named Cij. For instance, the channel from P1 to P2 is C12, while the channel from P2 to P1 is C21. A *snapshot* is a recording of the state of each process (i.e., what events have happened on it) and each channel (i.e., what messages have passed through it). The Chandy-Lamport algorithm ensures that when all these pieces are stitched together, they "make sense": in particular, it ensures that for any event that's recorded somewhere in the snapshot, any events that *happened before* that event in the distributed execution are also recorded in the snapshot.

The setup

Here's the execution we're going to be snapshotting. There are three processes, each with several events, including messages sent and received. Dots on process lines with no incoming or outgoing arrows are internal events.



One of the especially cool things about the Chandy-Lamport algorithm is that it is decentralized — any process (or multiple processes at once!) can begin taking a snapshot without coordinating with other processes. It doesn't cause problems to have multiple processes simultaneously begin taking a snapshot. For this example, though, we'll say that a single process, P1, initiates the snapshot. Let's suppose that P1 initiates the snapshot right after event B has happened.

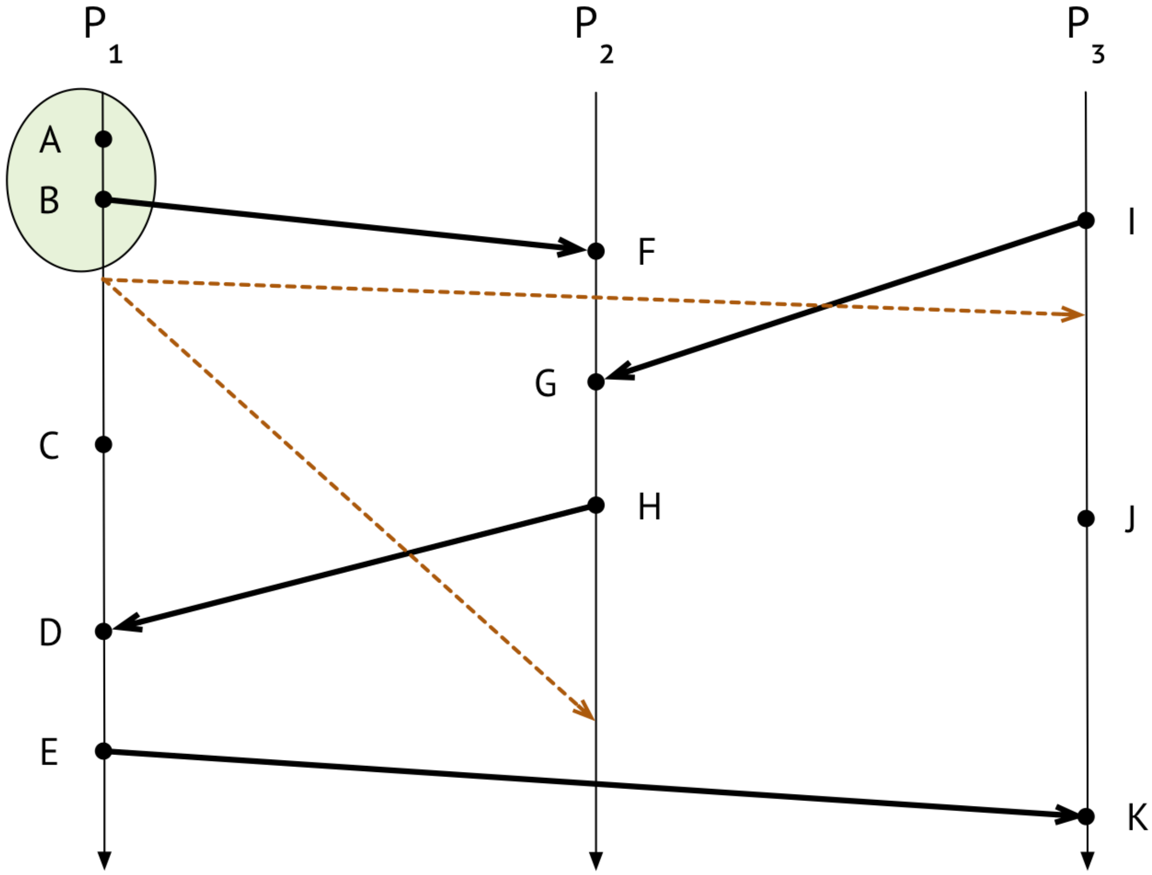
Initiating a snapshot

To get a snapshot started, an initiating process has to do three things:

- First, it has to *record its own state*. Because we're initiating the snapshot right after event B, the recorded state of P1 contains the events A and B. We'll circle those events to show that they're recorded.
- Next — immediately after recording its own state, and before it does anything else — it has to send a *marker message* out on each of its outgoing channels. A marker message is sent as part of the snapshot algorithm itself, as opposed to what I'll call *application* messages, which are part of the system we're taking a snapshot of. (Marker messages should not themselves be part of the state that the snapshot algorithm is trying to record; we'd like the snapshot we're recording to not include any artifacts from the snapshot-taking process, if we can help it!) In this case, P1 sends marker messages on channels C12 and C13, respectively.
- Finally, it needs to start keeping track of the messages it receives on all of its *incoming* channels. In this case, P1 has two incoming channels, C21 and C31. So, P1 starts recording incoming messages on those channels.

Now, things look like this:

C_{21} = *...recording...*
C_{31} = *...recording...*



We’ve recorded P1’s state, sent marker messages out along C12 and C13, and started recording on C21 and C31. We’ve drawn the marker messages as dotted lines to tell them apart from application messages.

The marker message headed to P2 is taking its sweet time to get there. Meanwhile, the marker messge sent to P3 arrives pretty quickly, so let’s talk about what happens when it arrives!

Receiving a marker message: the “this is the first marker message I’ve ever seen” case

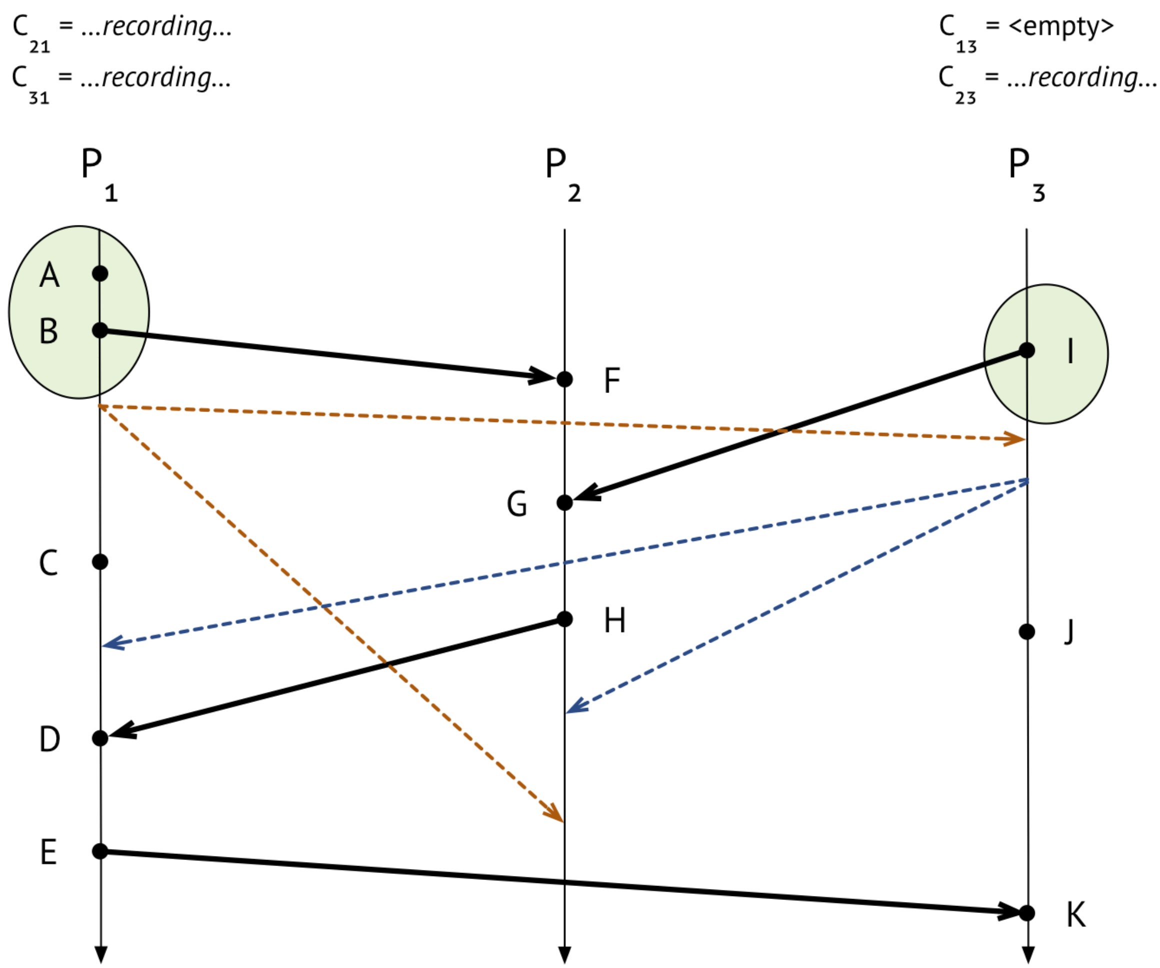
When a process Pi *receives* a marker message on channel Cki, there are two possibilities: either this is the first marker message that Pi has ever seen, or it isn’t. If it’s the first marker message that Pi has ever seen, then Pi needs to do the following:

- Record its own state.
- Mark the channel that the marker message came in on, Cki, as *empty*. No more messages can come in on that channel. Or, well, they *can*, but we won’t be recording them, and so they won’t be part of the snapshot.
- Send marker messages out itself, on all its outgoing channels.

- Start recording incoming messages on all its incoming channels *except* Cki, the one that it just marked as empty.

Is the marker message from P1 the first marker message that P3 has ever seen? Yes! So P3 duly follows the above steps. It records its own state, which only includes one event, I. It marks channel C13 as empty, because that's the channel the marker message came in on, and it sends its own marker messages on its outgoing channels to P1 and P2. It also starts recording incoming messages on all its incoming channnels except the one it just received the marker on. Because P3 only has two incoming channels, C13 and C23, and it received the marker on C13, it only has to start recording on C23.

Now things look like this:



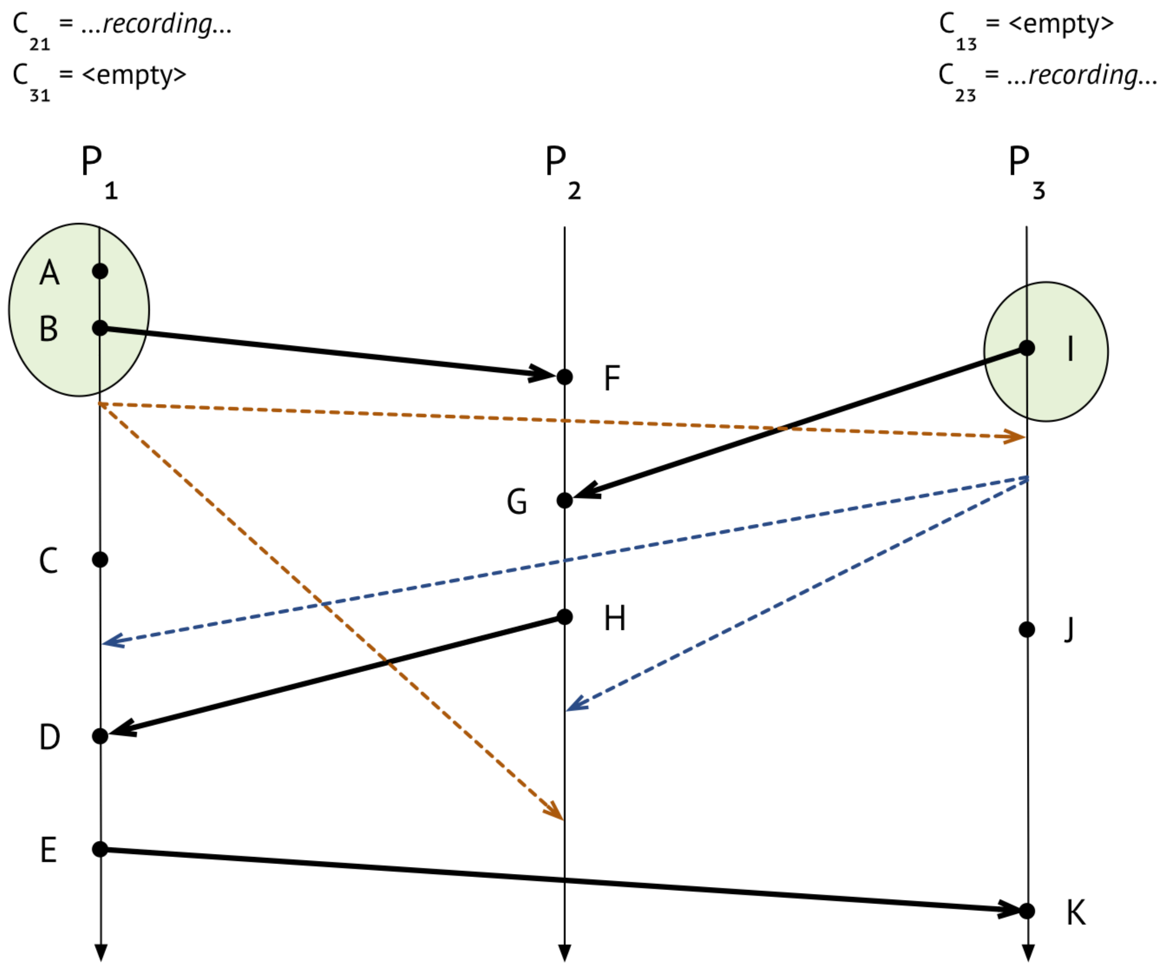
Yay! We've already recorded the states of two out of three processes! We're on our way to being done.

Receiving a marker message: the "this ain't my first rodeo" case

P3 has sent out its marker messages. Let's consider the one that went to P1 first. Is this the marker message the first that P1 has seen? No, because P1 was the first process to *send* marker messages in the first place! (Sending a marker message counts as "seeing" one.)

Here's what a process Pi should do when it receives a marker message on Cki that is *not* the first marker message it's ever seen: it should *stop recording* on Cki (note that it would have started recording on Cki back when it saw its first marker message), and it should set Cki's final state as the sequence of all the messages that arrived on Cki since recording began. That's it!

So, P1 can now stop recording on channel C31. It turns out it didn't receive any messages on that channel during the time it was recording, anyway. So C31's final recorded state is just the empty sequence.



Finishing up

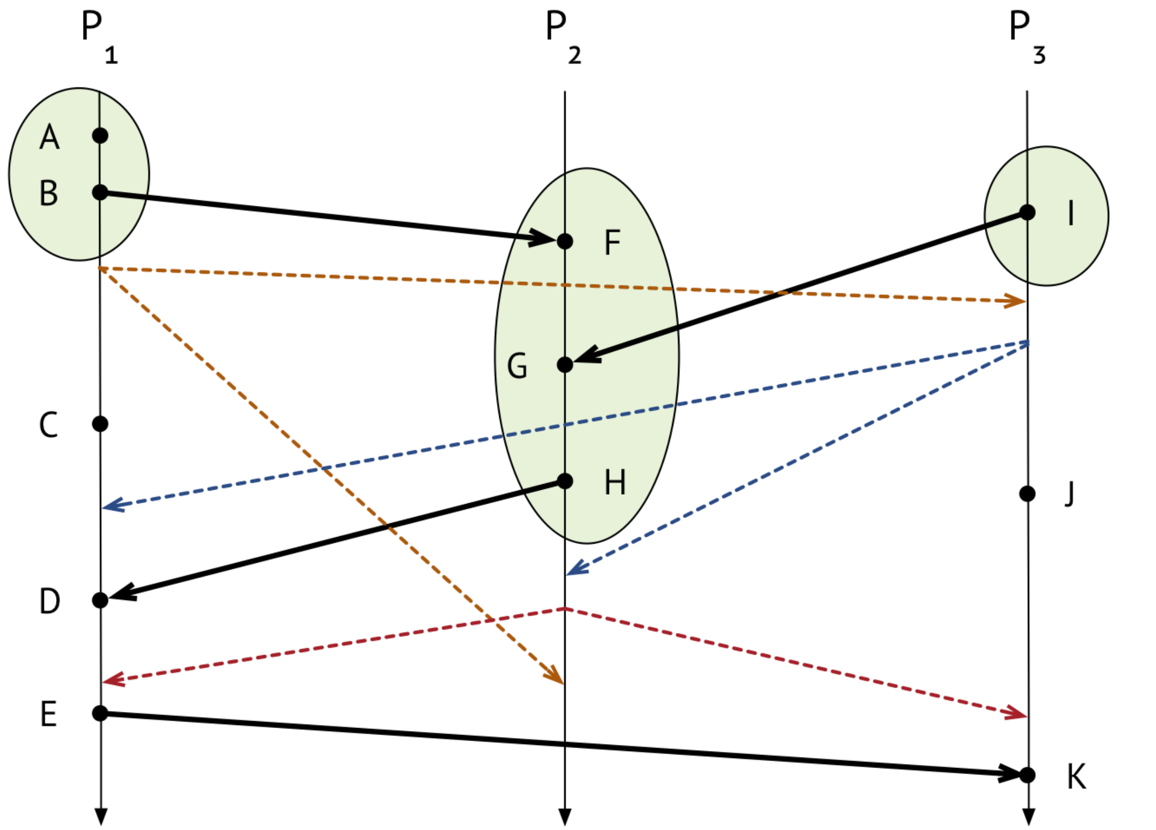
Now we can look at the marker message sent from P3 to P2. What does P2 do when it gets the marker message? It's the first marker message that P2 has seen, so P2 records its state, which includes events F, G, and H. It also marks the channel that the marker message came in on, C32, as empty; sends out its own markers on its outgoing channels to P1 and P3; and starts recording on every incoming channel except C32, the one it got the marker message on — so, just C12.

Now every process has recorded its state! Our picture looks like this:

C_{21} = *...recording...*
C_{31} = <empty>

C_{12} = *...recording...*
C_{32} = <empty>

C_{13} = <empty>
C_{23} = *...recording...*



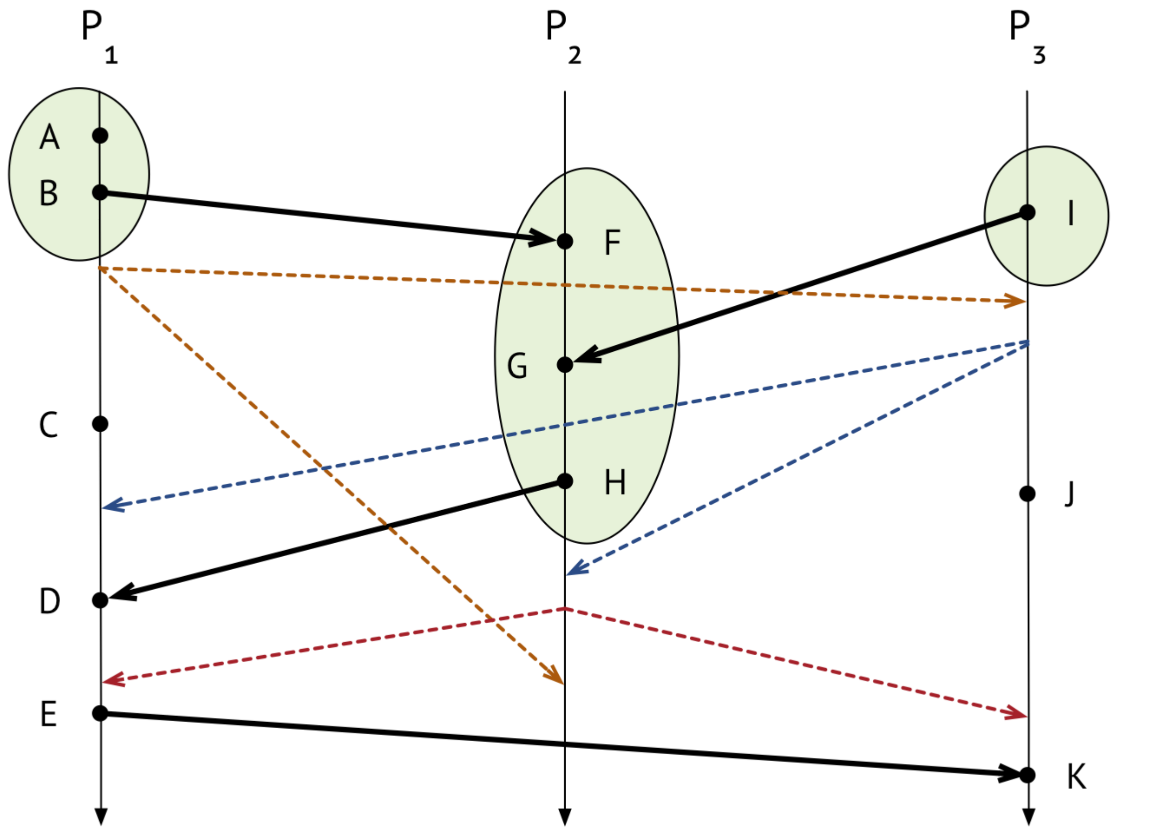
But we’re not quite done. Now that marker message that P1 sent to P2 approximately forever ago has finally arrived. Because P2 has seen a marker message before, it can now stop recording on channel C12 (which it only just started recording on). No messages were received during the recording period, so C12’s final recorded state is empty, too.

P2’s role in taking the snapshot is now completely done: it’s recorded its own state and that of both its incoming channels.

C_{21} = *...recording...*
C_{31} = <empty>

C_{12} = <empty>
C_{32} = <empty>

C_{13} = <empty>
C_{23} = *...recording...*



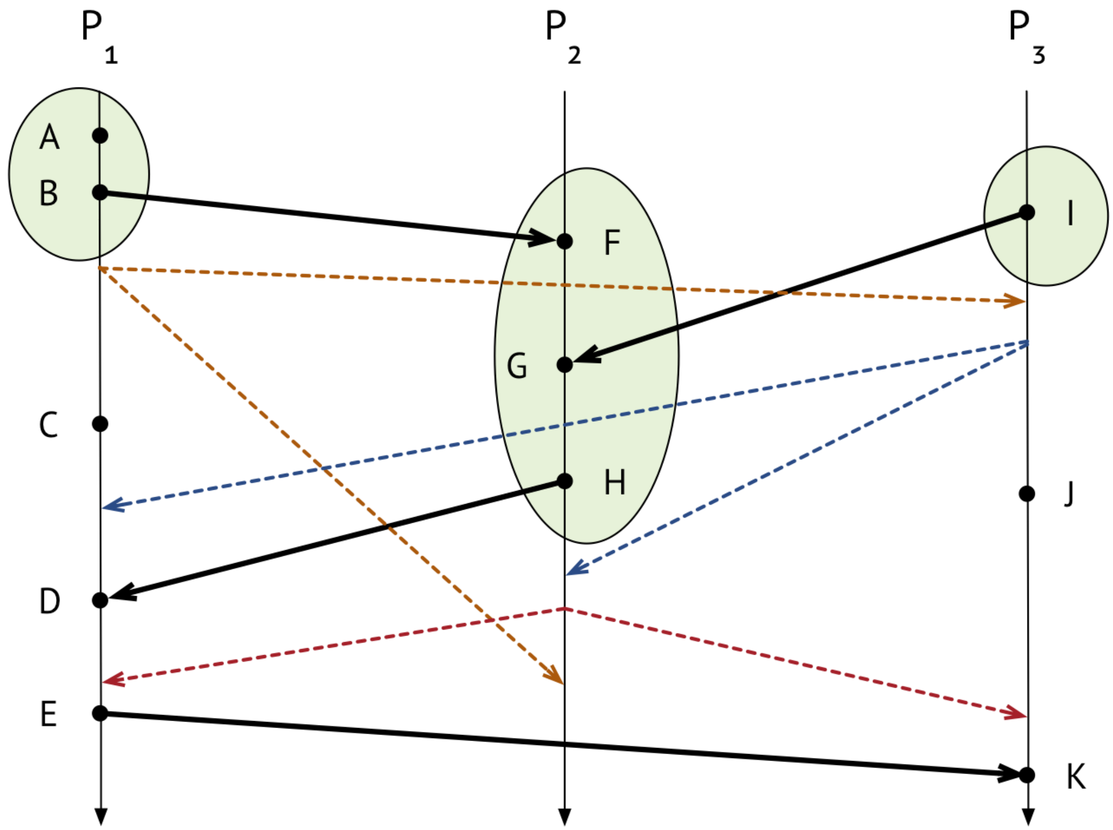
P1 still has to finish up, though. It’s waiting for a marker message to come in from P2, so it can stop recording on channel C21. Hey, look — that marker message just came in!

Did any messages get recorded on C21? Yes! The message whose send event was H and whose receive event was D did. So that event goes into C21’s final channel state.

C_{21} = [H→D]
C_{31} = <empty>

C_{12} = <empty>
C_{32} = <empty>

C_{13} = <empty>
C_{23} = *...recording...*

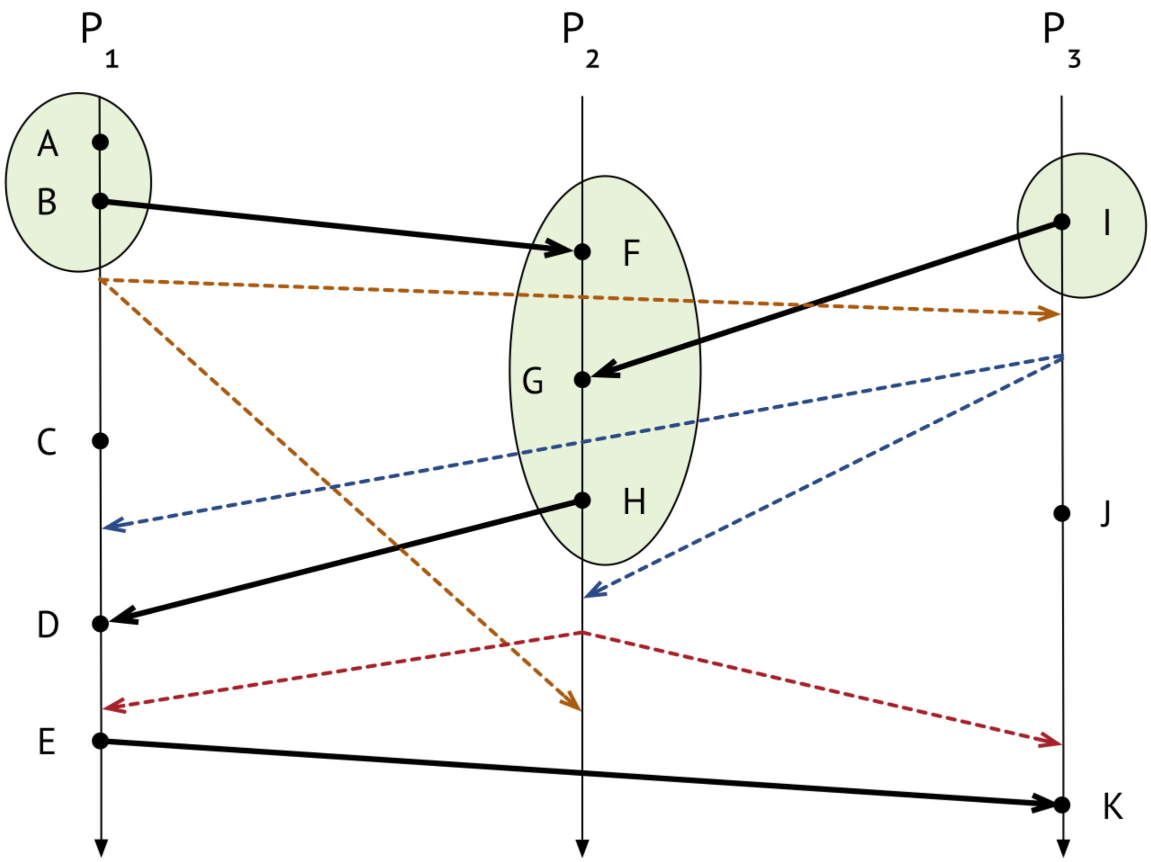


And finally, P3 gets the last marker that *it* was waiting for, from P2, and the final state of C23 can be set to empty because no messages came in while we were recording on that channel.

C_{21} = [H→D]
C_{31} = <empty>

C_{12} = <empty>
C_{32} = <empty>

C_{13} = <empty>
C_{23} = <empty>

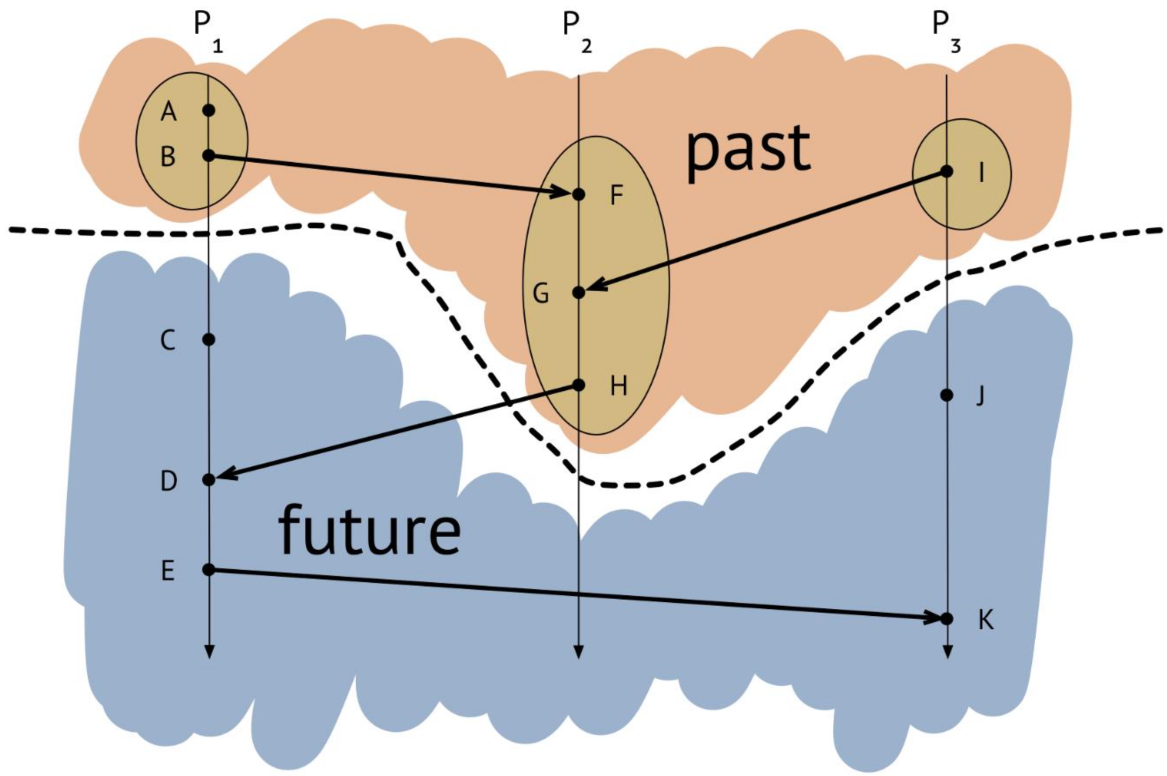


Now, all the processes' states *and* all the channels' states have been recorded, so we can say that we're done!

Discussion

Now that we're done taking the snapshot, we can ignore the marker messages and just look at the state we recorded. We said earlier that a property we want to have be true of any snapshot we take is that, for any event recorded somewhere in the snapshot, any events that *happened before* that event in the distributed execution should also be recorded in the snapshot.

We can see that that's true of the snapshot we just took: for every circled event, if we look at the events in its causal history, those events are all in the snapshot as well. In other words, the snapshot produces a *consistent cut* in our diagram, where every message received on the "past" side of the cut was sent on the "past" side, and no messages go backwards in time.



A student asked me whether event D counts as part of the recorded state, because it's the receive event for the message from H to D that we recorded on C21. We should *not* consider D to be part of the recorded *process* state. (In fact, in our example we have event C hanging out on P1 in D's causal history, so if D were in the snapshot, then C would have to be as well for it to be a consistent snapshot.)

So, what's the point of recording channel states, then? Well, imagine that we want at most one process in this execution to have exclusive access to some sort of resource (say, a file). We can think of access to the resource as being a *token* that processes pass around. At any given time, either a process should have the token, or it should be in transit between processes.

Suppose that P2 has the token and then decides to hand it off to P1. The message sent at H and received at D might say, "I'm passing the token to you." If this were the case, then the process state at P2 was recorded *after* P2 gave up the token, but the process state at P1 was recorded *before* P1 got the token. This isn't great — it means that, for anyone looking at only the recorded process states, the token seems to have disappeared! Recording the channel states addresses this problem: since the message from H to D is part of the recorded channel state, someone looking at the snapshot can inspect the contents of the message and see that when the snapshot was taken, the token was *in transit* from P2 to P1, maintaining the invariant that there should be one token in the system.

Practical Applications

Google Spanner system is a distributed system that provides snapshot read isolation, which might be one practical example of snapshotting algorithms: http://static.googleusercontent.com/media/research.google.com/en/us/archive/spanner-osdi2012.pdf

HP uses this kind of algorithms for rollback-recovery protocol for crash/recover hosts and fair-loss links. you can find an interesting article about that here:
http://www.hpl.hp.com/techreports/2010/HPL-2010-155.pdf

GRID: Another major example can be: "State of termination". Let's say you are running heavy computations which are split among your distributed systems. You can know the termination state if you take snapshot twice and compare and find the local state of the channel, as well as the systems/processes, are same.

Apache Flink makes use of a distributed snapshot algorithm (for checkpointing) very similar to the Chandy Lamport. A marker is sent across the network that signals to the nodes they need to record their state with the slight difference that the state of the channels is not recorded.
The following two papers contain more information on this:

- Lightweight Asynchronous Snapshots for Distributed Dataflows (link)
- State Management in Apache Flink (link)