Consensus

(And View Synchronisation)

Andrew Lewis-Pye, 28th June 2022

Joint work with Ittai Abraham:
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Combined with Hotstuff, this gives the first optimistically response blockchain protocol functioning in the partially synchronous setting which has:

- $O(n)$ complexity per confirmed block in the optimistic case;
- $O(n^2)$ complexity per confirmed block in the worst case.

A LITTLE PUZZLE FOR THOSE WHO KNOW CONSENSUS

Consider the synchronous setting, authenticated channels, Byzantine faults, PKI. Can you design a deterministic protocol to solve Byzantine Broadcast, in which each party speaks at most once?

'Speaking once' means that each party can send multiple messages, but they must all be sent at the same timeslot.

What is the problem a consensus protocol has to solve?

THE BYZANTINE AGREEMENT PROBLEM (INFORMAL)

Several divisions of the Byzantine army are camped outside an enemy city, each division commanded by its own general. The generals can only communicate by messenger and must carry out a protocol to decide on a common plan of action, either 'retreat' or 'attack'. Initially, each general has their own private opinion as to the best plan of action. The difficulty is that some unknown subset of the generals may be dishonest traitors (and may deviate from the protocol). The protocol must satisfy:

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(1) **Termination.** Each honest general must eventually reach a decision (retreat or attack).
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Without validity requirement, it would be trivial.

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There are n parties (generals), of which at most f are dishonest. Each starts with their own input. Must satisfy:

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For clarity, suppose the honest generals know f (but not which are the dishonest generals).

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So, it is clear that one of the basic questions we should be interested in is "what values of n and f can a protocol handle?".

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Attack

Retreat

Output: Attack

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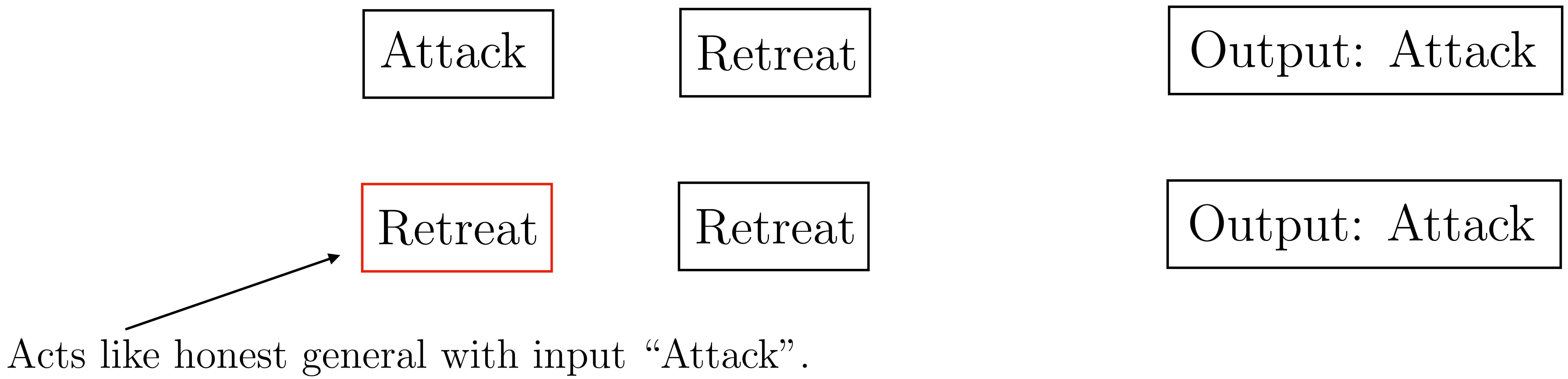

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The problem with this approach stems from the allowed form of communication between generals (which is intended to accurately reflect communication between processors in real world scenarios).

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If the generals were standing in a circle and shouting out their votes – so that everybody can see who is shouting out a vote and any vote heard by a single honest general is immediately heard by all – then a simple majority vote approach would work. In the setting described above, however, communication occurs by messenger between one pair of generals at a time.

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The problem now is that dishonest generals can tell different things to different generals. Suppose $n = 3$ and $f = 1$. One honest general initially wants to attack, while the other wants to retreat. If the dishonest general sends a 'retreat' message to the general who wants to retreat and an 'attack' message to the general who wants to attack, then the honest generals will see different majority votes.

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In fact, we will see that (under a natural formalisation of the informal problem above) the Byzantine Agreement problem is not solvable when $f \geq n/3$ unless we endow the generals with certain extra abilities. So the problem is not as trivial as it might initially seem.

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- There are n processors given names 0 to $n-1$. Each processor is told n as well as their own name i, i.e. this information is given as part of their input.

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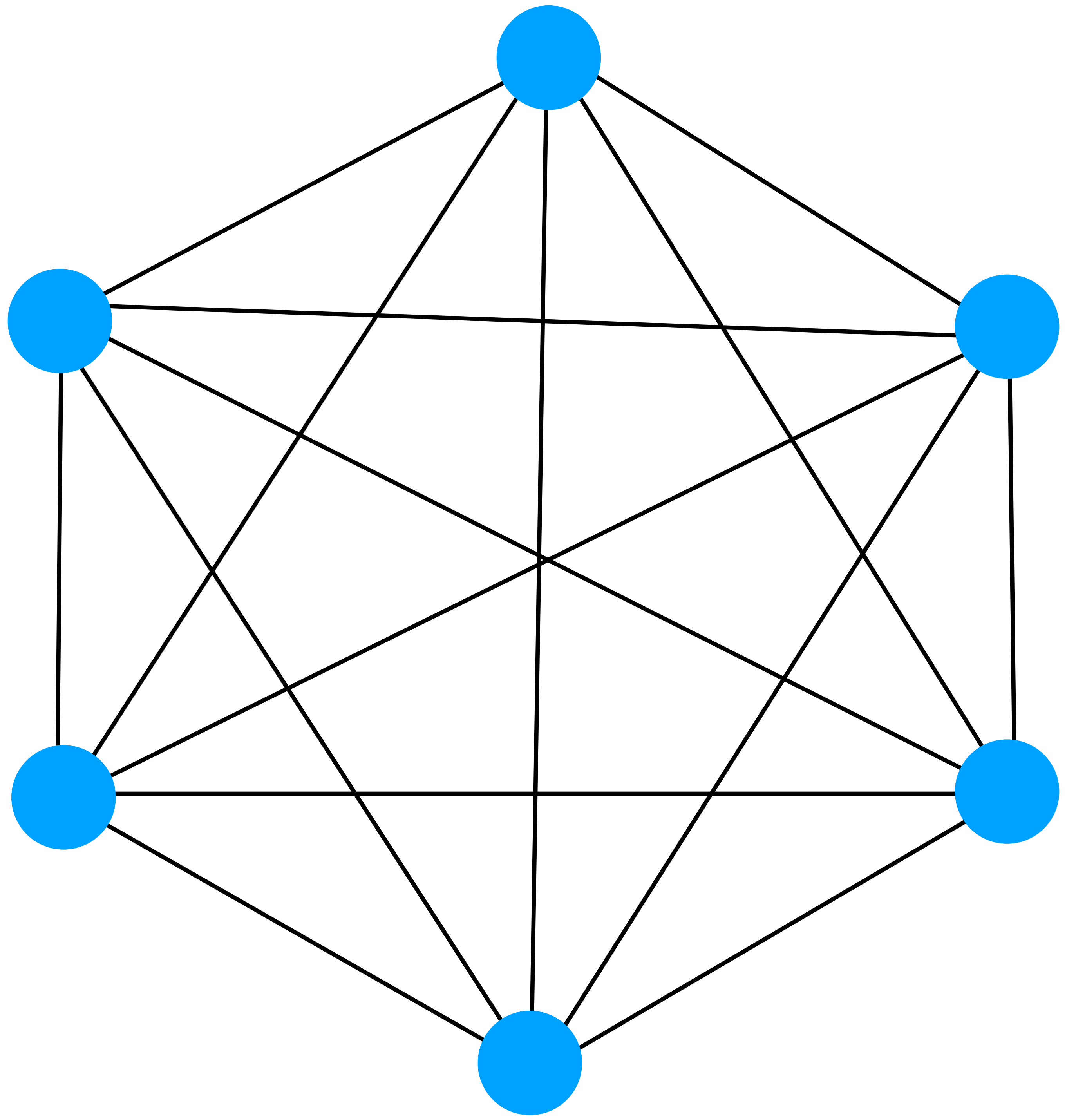
Authenticated channels. There exists a two-way authenticated communication channel $\{i, j\}$ for each pair of distinct processors i and j:

- Only i can send messages to j and only j can send messages to i on the channel $\{i, j\}$, and;



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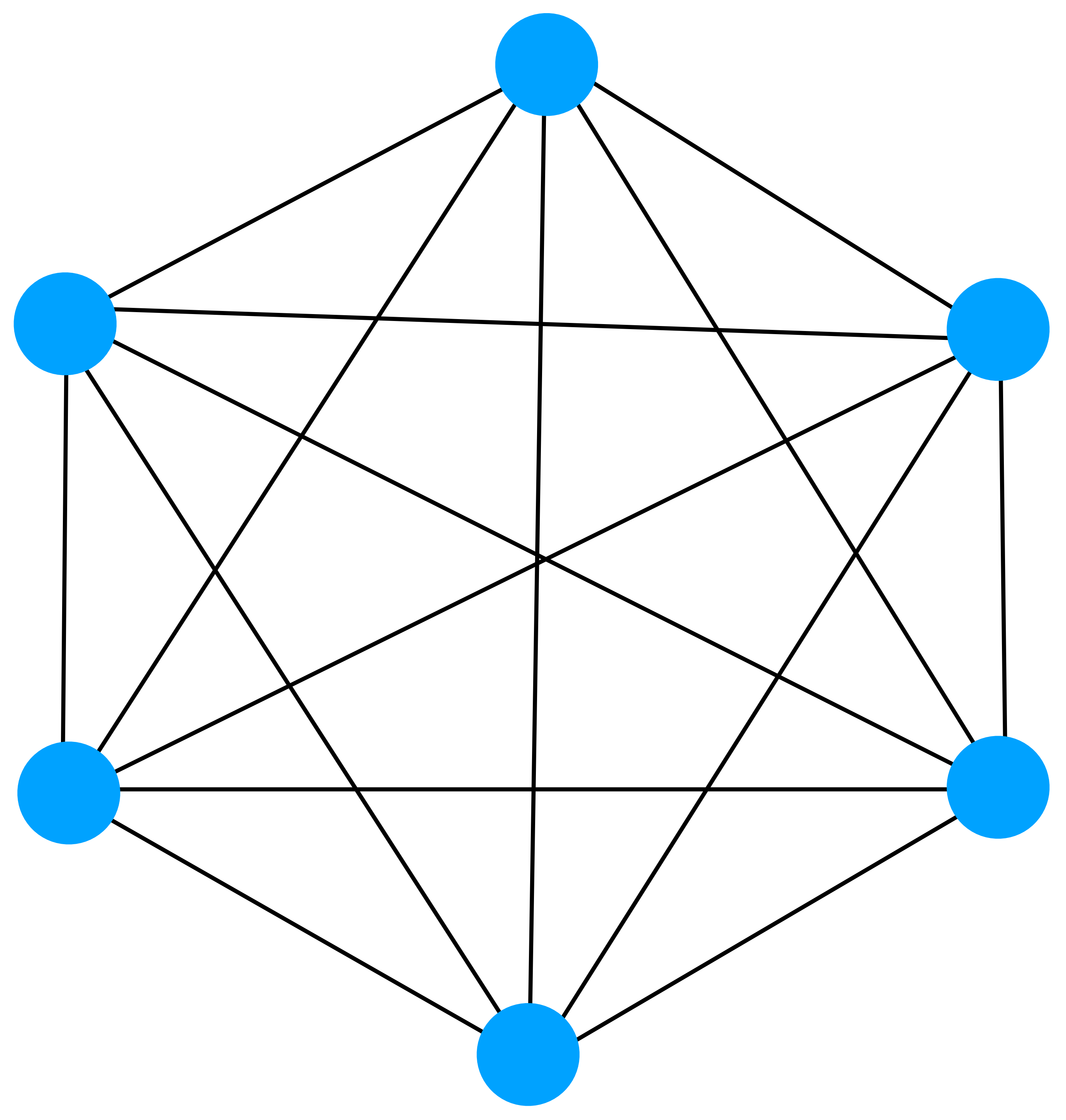

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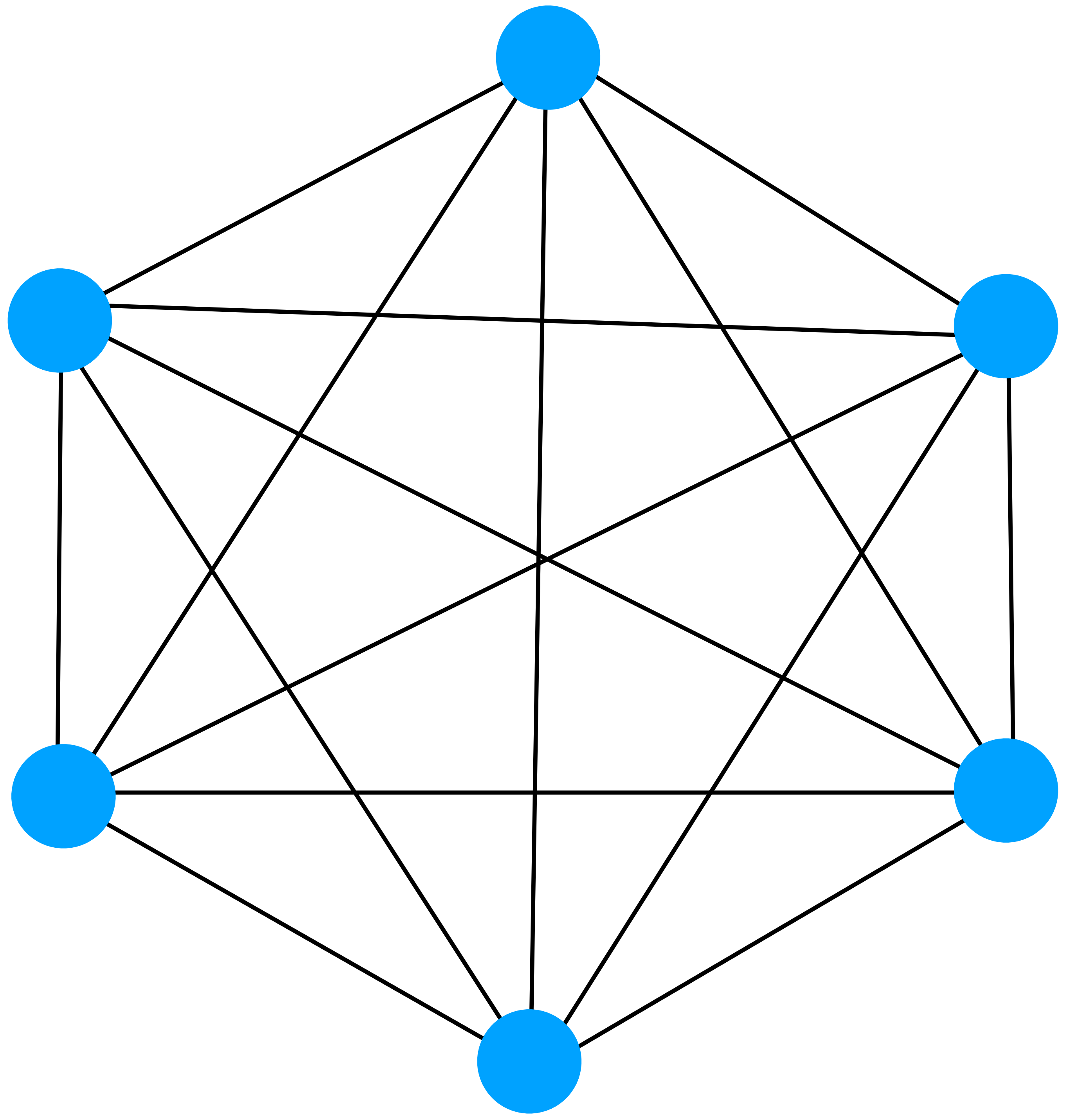
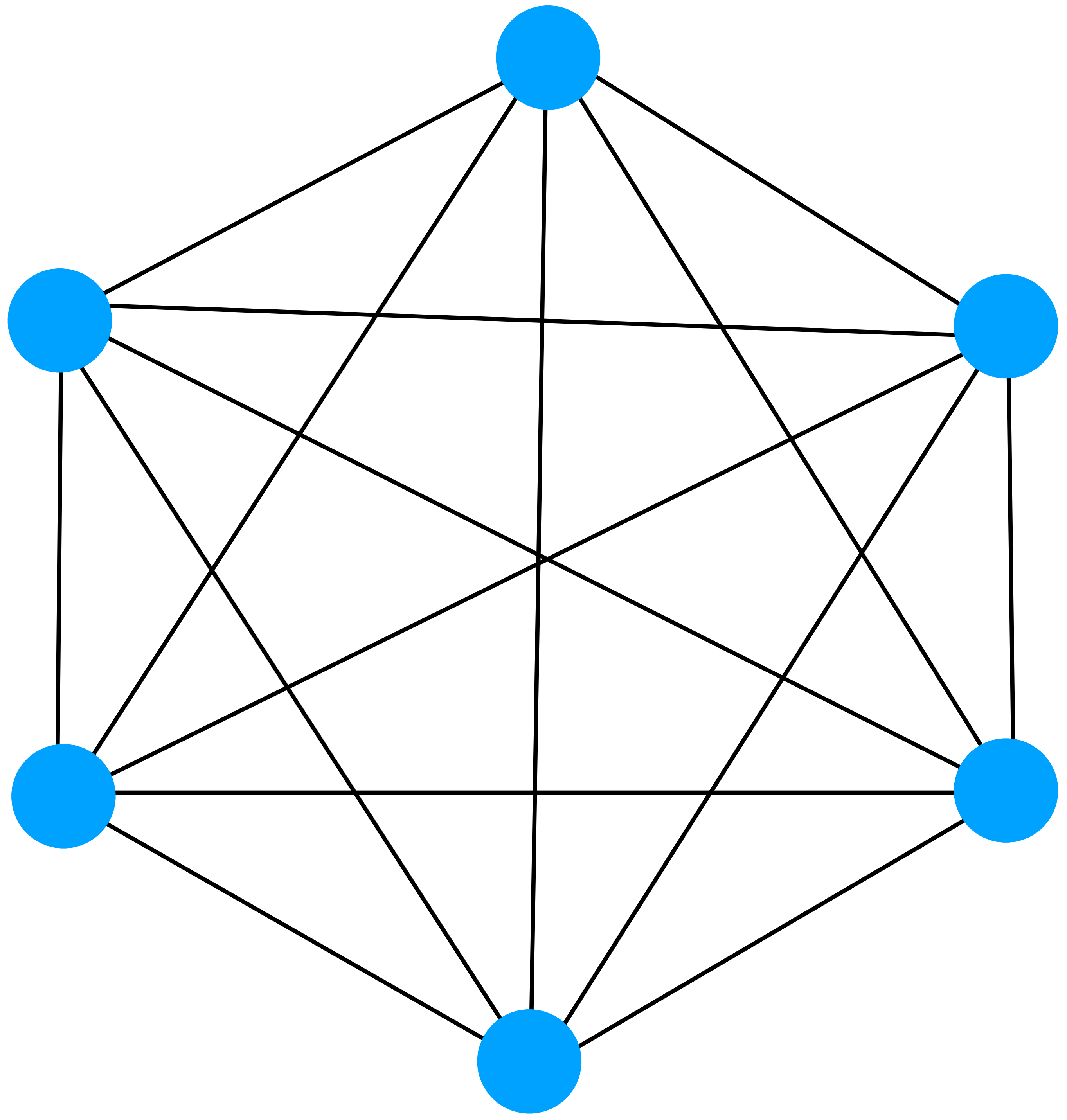


At each timeslot, the instructions for processor i determine which messages it should send along each of its channels $\{i, j\}$.

THE FORMAL FRAMEWORK

Public Key Infrastructure (PKI). Sometimes we'll assume given a PKI, sometimes not. If given a PKI, this means each processor is provided with a $(\mathrm{sk}, \mathrm{pk})$ pair, and is told the public key of each of the other processors.



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Message delay and the synchronous setting. To keep things simple, we start by considering what is known as the *synchronous* setting. This means that if i sends j a message at time t then j receives that message from i at time $t + 1$.

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Crash faults. Sometimes we will also be interested in a more benign form of faulty behaviour known as *crash faults*. In the crash fault setting, faulty processors must follow the protocol precisely until such a point as they crash, whereupon they execute no further instructions.

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What is the relationship between the Byzantine Agreement (BA) problem and the Byzantine Broadcast (BB) problem? We saw BA cannot be solved when $f \geq n/2$. It is easy to see, though, that the same argument doesn't apply to BB – in fact, we'll see that, if a PKI is given and we work in the synchronous setting, then BB can actually be solved for any number of faulty processors.

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So, there are certainly scenarios in which BB can be solved although BA cannot be.

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On the other hand, if we work in the synchronous setting and if $f < n/2$ then the two problems reduce to each other quite easily:

- If we can solve BB, then to solve BA we have all processors broadcast their inputs using the protocol for BB (meaning that we carry out n simultaneous executions of BB). Once a value is decided corresponding to each processor, processors then decide by majority vote, breaking ties in some previously arranged but arbitrary fashion.

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- If we can solve BA, then to solve BB we have the broadcaster send their input to all other processors at time 0. Each processor then takes the value received at time 1 as their input value, choosing some arbitrary value in V if no value is received from the broadcaster. We then have the processors carry out the protocol for BA on those input values.

BA and BB: Synchronous setting with PKI

We'll prove the following:

Theorem. *Consider the synchronous setting with PKI given. There exists a protocol that solves the Byzantine Broadcast problem for any number of faulty processors.*

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This also deals with BA. By the reductions discussed before, the theorem also suffices to show that we can solve BA when working in the synchronous setting with PKI iff $f < n/2$.

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- If they only ever see a single value produced, then they output that value. If they ever see two different values produced, then they realise the broadcaster is faulty, so they give some 'default' value as output.

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- If they only ever see a single value produced, then they output that value. If they ever see two different values produced, then they realise the broadcaster is faulty, so they give some 'default' value as output.
- If the broadcaster is non-faulty then they will only produce a single signed value and all non-faulty processors will output that. If the broadcaster produces two different signed values and shows them to non-faulty processors then (the idea is) everyone will eventually see those values and give the default output.

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The problem. When should processors stop sharing values and terminate? If they share until time t, then the adversary can choose to show one signed value to all non-faulty processors until time t, and then show some subset of the non-faulty processors a second signed value at time t (when it is too late to share anymore), causing the 'agreement' requirement of BB to be violated.

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The trick. What we need is a clever mechanism to ensure that if any non-faulty processor ‘recognises’ a certain signed value produced by the broadcaster, then all non-faulty processors will also ‘recognise’ that value.

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That way, either they all recognise a single value and give that as output, or they all recognise multiple values and so give the default output.

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- Then we stipulate that if a processor is to 'recognise' a new value at any time t, the message must have been signed by t distinct processors. If they recognise a new value at time t, then they add their signature to the list and send that message (now with $t+1$ distinct signatures) to all other processors.

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- At time $f+1$ we give the processors a last chance to recognise new values (but not to share again) before either outputting the single value they have recognised or else a default value.

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Why does this approach work? We have to show that if any non-faulty processor recognises a certain value $v \in V$, then all non-faulty processors will also recognise that value. There are two cases to consider:

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- **Case 1**. Suppose that some non-faulty i first recognises v at a time $t < f + 1$. In this case, i receives a message relaying the value v at time t which has t distinct signatures attached. Processor i then adds their signature to form a message with $t + 1$ distinct signatures and sends this message to all processors. This means all non-faulty processors will recognise v by time $t + 1$ $(\leq f + 1)$.

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- **Case 2**. Suppose next that some non-faulty i first recognises v at time $f + 1$. In this case, i receives a message relaying the value v at timeslot $f + 1$ which has $f + 1$ distinct signatures attached. At least one of those signatures must be from a non-faulty processor j (since there are at most f faulty processors), meaning that Case 1 applies w.r.t. j.

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(2) Then extending it to the general case is also easy, if one doesn't care about the number of stages. Run DS for the first value of V first. If you 'recognise' the first value at the end of that, stop there and output.

    If not, then that means no honest processor (other than maybe the broadcaster) has spoken yet. So, run DS for the second value, and so on.

State Machine Replication

Very roughly, SMR is the problem that blockchain protocols are designed to solve: Clients send in a sequence of transactions of their choosing and the processors implementing the SMR protocol have to agree on an order in which to implement those transactions.

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- Could be interested in implementation in the permissioned setting.
- Permissioned protocols can be implemented as permissionless protocols (PoS) of a sort, and may be more efficient.
- Can function in the partially synchronous setting (where message delivery is less reliable).

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- Best known complexity per view change was $O(n^2)$.
- New method gives $O(n)$ view changes.

Joint work with Ittai Abraham

The underlying protocol. We suppose view synchronisation is required for some underlying protocol (such as Hotstuff) with the following properties:

- Instructions are divided into views. Each view v has a designated *leader*, denoted $\texttt{lead}(v)$.
- If the honest processors spend long enough in a view with an honest leader when network conditions are good, the view will complete successfully, and produce a 'certificate' (QC) signed by $n - f$ processors.

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The view synchronisation task:

- We have to ensure that all non-faulty processors eventually spend long enough in the same view that it completes successully.
- We also want a protocol which is *optimistically responsive*: i.e. can go as fast as the network can handle.

Clock-times. To synchronise processors while maintaining optimistic responsiveness, we have a predetermined 'clock-time' corresponding to each view: The clock-time corresponding to view v is $t_v := \Gamma v$. At certain points in the execution, a processor may instantaneously forward their clock to some clock-time t_v and enter view v.

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This will allow us to achieve view synchronisation. When an honest processor enters a new view v, they send a message to the leader telling them. Once the leader receives $f+1$ of these, it combines these into a 'start view v' message, telling other processors to start the view. The condition above means this will happen in sufficient time.

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- We see attestations from $n - f$ processors that they are at most Γ behind t (we see a QC for the previous view).
- We see attestations from $f + 1$ processors that their clock is $\geq t$ (we see a message saying we should start view v).

Inductively, it's easy to see that the safety condition will never be violated.

Thanks for listening!