Time

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The Problem

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Given a collection of processes that can...

- Only communicate with significant latency
- Only measure time intervals approximately
- Fail in various ways

...we want to construct a shared notion of time.

Why The Problem Is Interesting

Interesting for two reasons:

1. Good setting to examine general difficulties in distributed systems:
    - Fault tolerance
    - Consistent view of changing data
    - Trust
    - Interplay between strength of guarantees and practicality

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2. Useful primitive for distributed systems
    - Distributed checkpointing / stable property detection
    - Can be used to implement general state-machine algorithms reliably [Lamport 74]

Overview

We will discuss two papers that solve this problem:

1. Optimal Clock Synchronization [Srikanth and Toueg '87]
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    - Assume reliable network
    - Provide logical clock with optimal agreement
    - Also optimal with respect to failures
2. Probabilistic Internal Clock Synchronization [Cristian and Fetzer '03]
    - Drop requirements on network
    - Provide very efficient logical clock
    - Only provide probabilistic guarantees

Some Assumptions

We assume. . .

- Clock drift is bounded:

$$\frac{1}{1+\rho}(t_2 - t_1) \leq R_i(t_2) - R_i(t_1) \leq (1+\rho)(t_2 - t_1)$$

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- Authenticated messages (we will relax this later).

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- Optimal accuracy (proved later):

$$\gamma = \rho$$

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Definitions: A *correct* process follows the protocol and has a working hardware clock. A non-correct process is *faulty*.

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- The kth resynch period is the interval $[beg^k, end^k]$

Outline of Proof of Agreement

Sketch of Agreement:

- Proof is by induction on round number k.
- Show that if kth clocks agree then $(k+1)$st clocks also agree
- Uses bounds on sizes of intervals between rounds and within rounds.

Outline of Proof of Accuracy

We prove the two defining inequalities for accuracy separately:

- By considering the fastest possible clock and showing it forms an upper bound on any logical clock value, we can show

$$C_i^k(t) \leq \frac{P}{P-\alpha}(1+\rho)t + b$$

- Similarly, considering slowest possible clock yields

$$\frac{P}{P-\alpha+[t_{del}/(1+\rho)]}(1+\rho)^{-1}t + a \leq C_i^k(t)$$

- Putting these together we get Accuracy, which in turn gives correctness.

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- Taking $t \to \infty$ we see $\gamma \geq \rho$.

An Optimal Algorithm Drift-wise

Key insight:

- There's an interval of uncertainty in difference between arrival time:
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Proof of correctness goes through mostly unmodified, but drift rate is optimal.

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Thus this algorithm is optimal with respect to fault tolerance.

Extensions to the Basic Algorithm

We can remove some of the limitations from the basic algorithm:

- Strong authentication is too heavyweight. Only need:
    - Correctness
    - Unforgeability
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  - Integration
- Can merge new clocks into a single continuous clock

Motivation for Probabilistic Synchronization

The Optimal scheme has some problems:

- Relies on guaranteed timely delivery (may not be an option)
- Performance depends on t_{del}, which can be large
- Bursty $O(n^2)$ messaging

Can we do without these limitations?

Probabilistic System Model

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- No longer a maximum communication delay
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  - this prevents us from stating results in terms of t_{max}.
- There is a known minimum message delay t_{min}

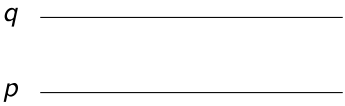
Failure Models

We distinguish between:

- Crash failure — process stops completely
- Performance failure — process runs too slow
- Read failure — process fails to read remote clock in time
- Arbitrary failure — anything else

Probabilistic Remote Clock Reading

How does process p read process q's clock?



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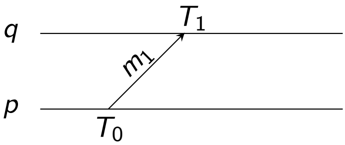

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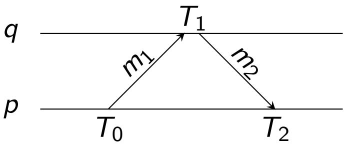

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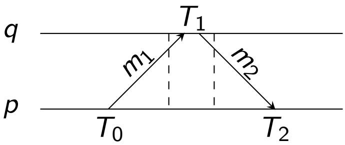

1. p sends a request m_1 with timestamp T_0 to q
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3. p can infer that T_1 is in a certain interval.

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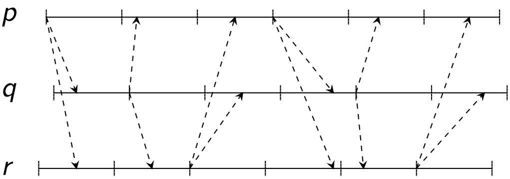
- Likely Success

Note that these are also satisfied by deterministic clock reading

The High Level Algorithm

The synchronization algorithm is organized as follows:

- A *slot* is a unit in which a single process gets to send



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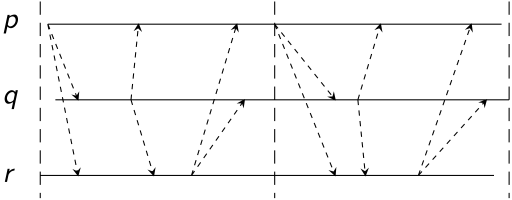

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- A *slot* is a unit in which a single process gets to send
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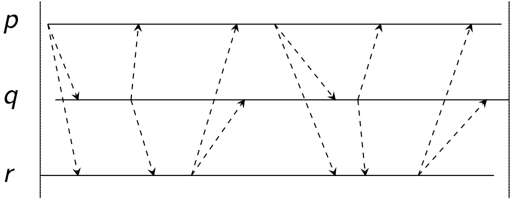
- A *round* is a unit in which all processes must get estimates of other clocks



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If q trusts p can also use it to approximate other clocks.

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Total message complexity is kN in the worst case, $N+1$ in the best.

From Approximations to Shared Time

Thus far *p* has a separate approximation of everyone's clock, with error bounds.

We plug the data into a *midpoint convergence function*, which:

- Combines the estimates of the clocks to yield a single value
- Is responsible for detecting and correcting errors
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The authors provide four algorithms:

- Crash-fail (requires $n \geq f + 1$)
- Read-fail (requires $n \geq 2f + 1$)
- Arbitrary-fail (requires $n \geq 3f + 1$)
- Hybrid-fail (requires $n \geq 3f_A + 2f_R + f_C + 1$)

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