Preventing (Network) Time Travel with Chronos

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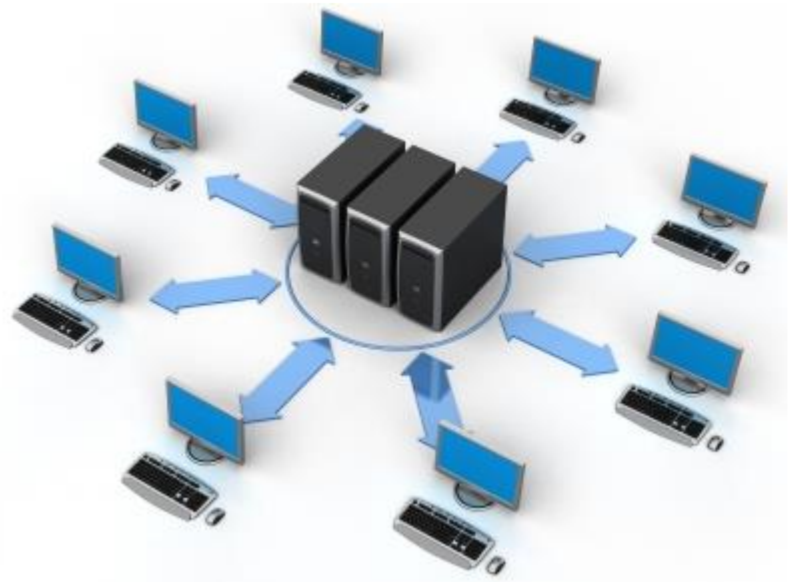
Network Time Protocol (NTP)

- NTP synchronizes time across computer systems over the Internet.

- Many applications rely on NTP for correctness and safety:
    - TLS certificates
    - DNS (and DNSSEC)
    - HTTPS
    - Kerberos
    - Financial applications



NTP Architecture

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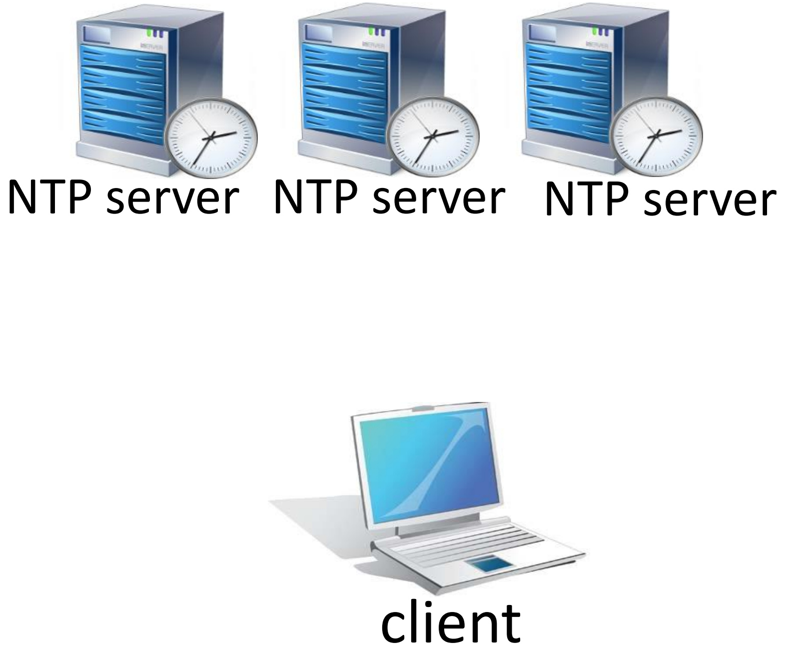

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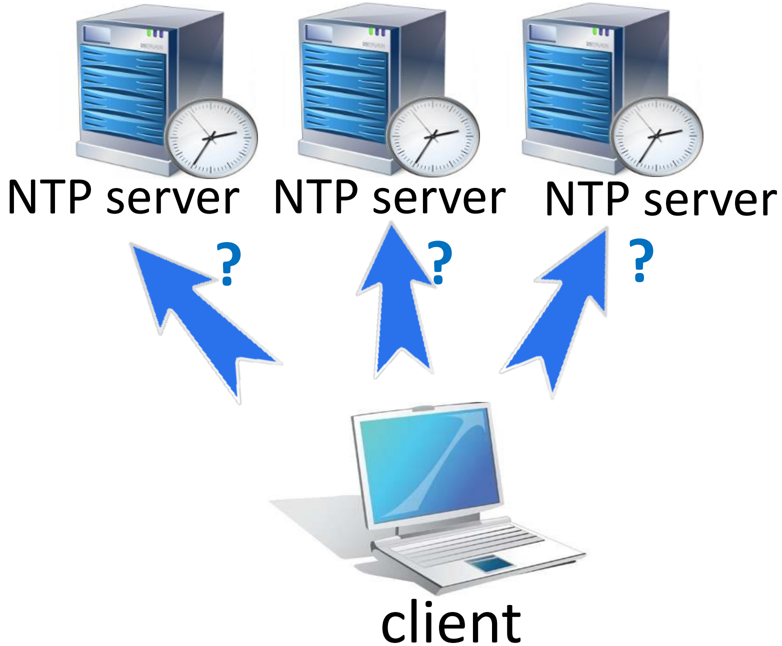

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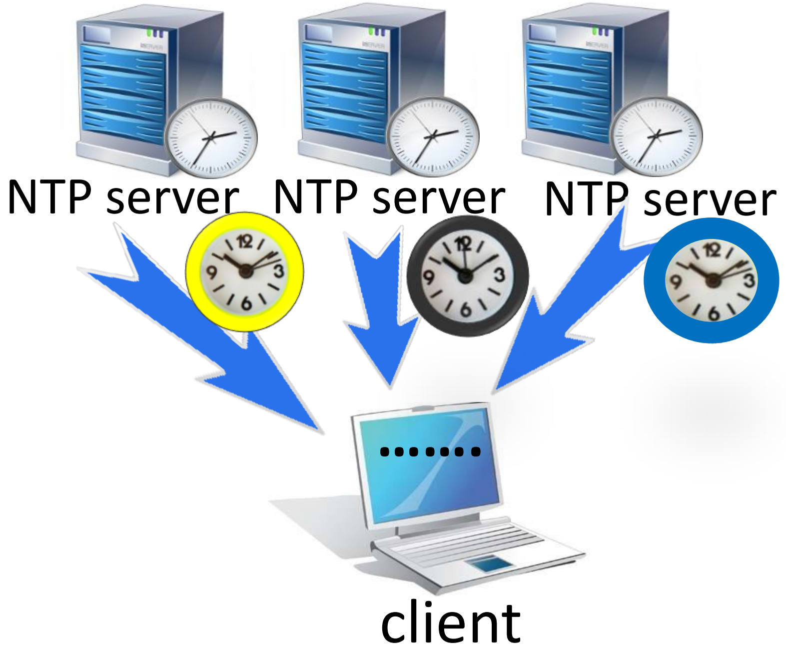

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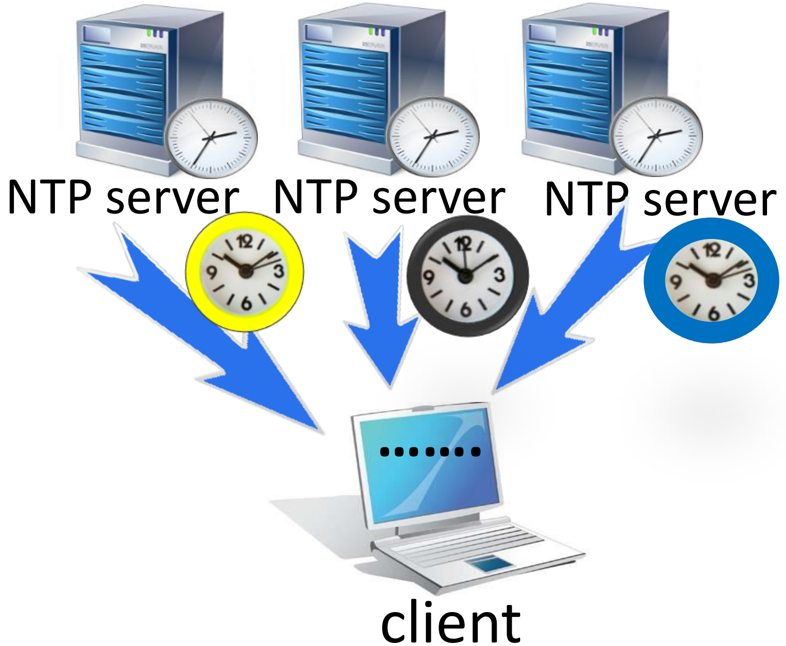

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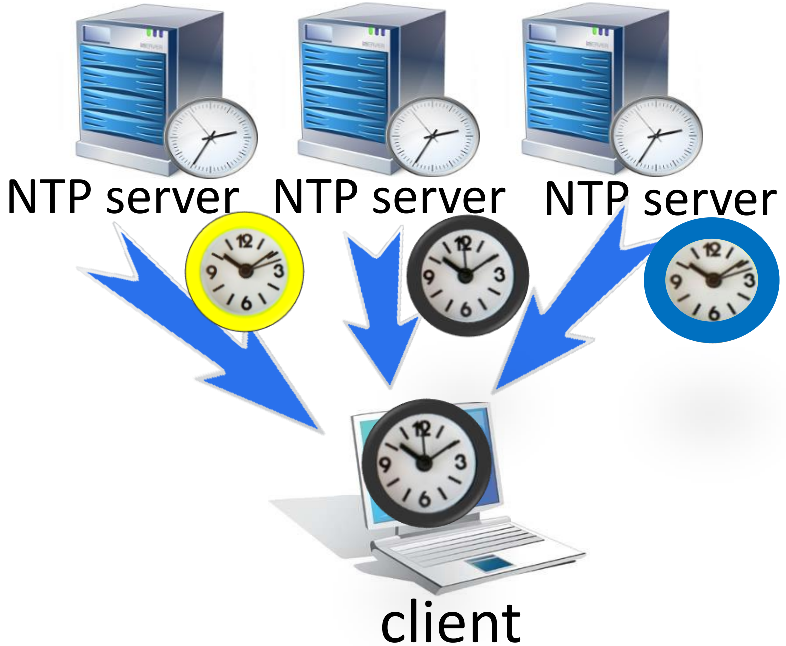

NTP Man-in-the-Middle (MitM) Attack

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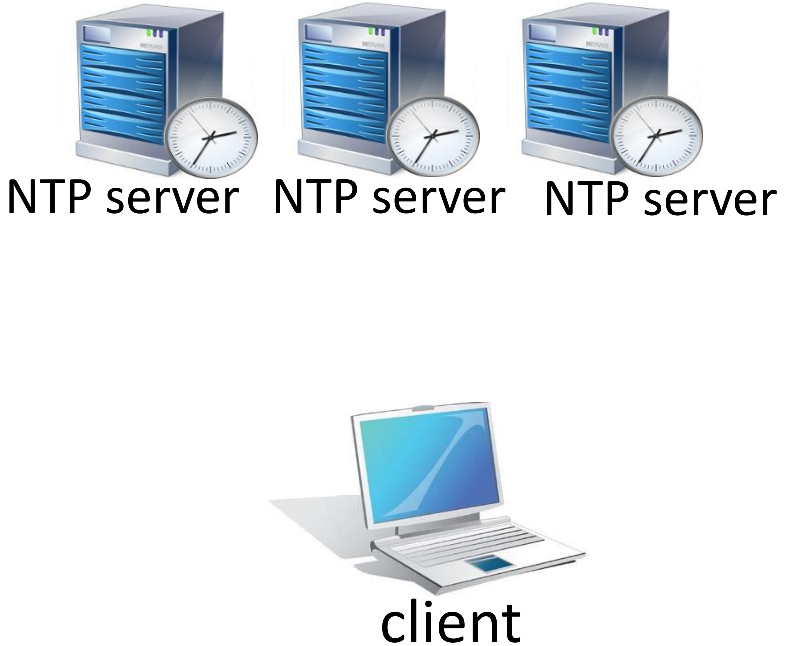

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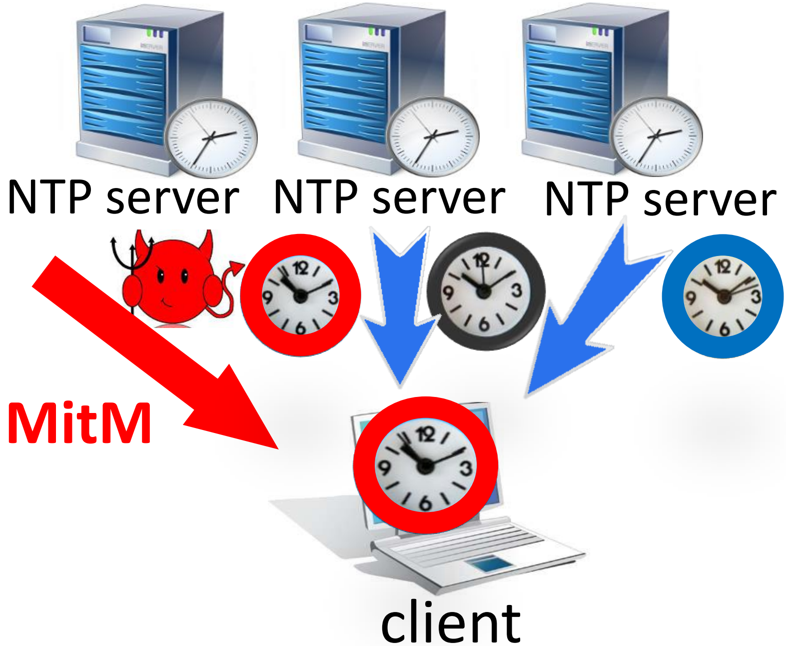
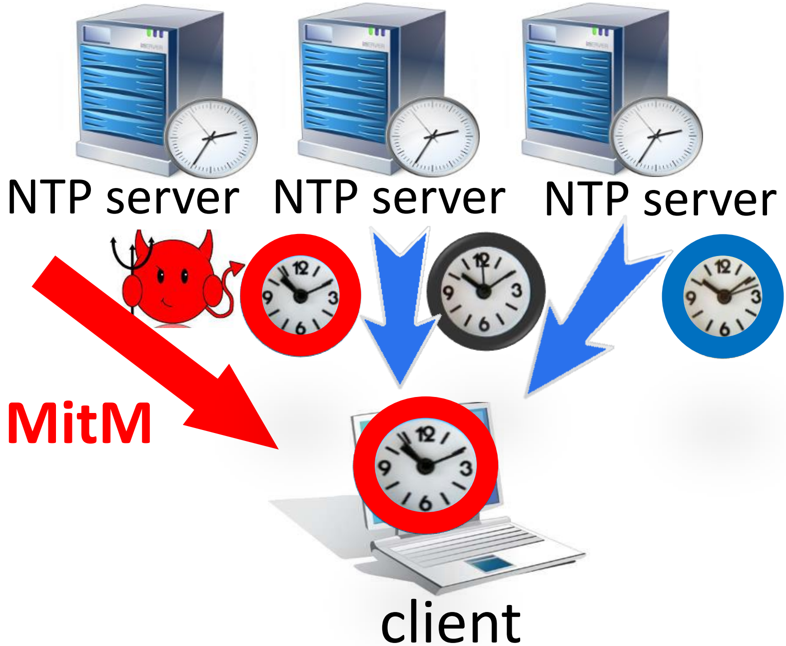


NTP Man-in-the-Middle (MitM) Attack

- NTP is highly vulnerable to time shifting attacks, especially by a MitM attacker
    - Can tamper with NTP responses
    - Can impact local time at client simply by dropping and delaying packets to/from servers **(encryption and authentication are insufficient)**

- Previous studies consider MitM as "too strong for NTP"



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Powerful and sophisticated MitM attackers are beyond the scope of **<u>traditional</u>** threat models

Chronos to the Rescue

The **Chronos NTP client** is designed to achieve the following:

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- **Backwards-compatibility**
  - ➢ no changes to NTP servers
  - ➢ limited software changes to client
- **Low computational and communication overhead**
  - ➢ query few NTP servers

Threat Model

The attacker:

- Controls a large fraction of the NTP servers in the pool (say, ¼)
- Capable of both modifying the content of NTP responses **<u>and</u>** timing when responses arrive at the client
- Malicious

Chronos Architecture

Chronos' design combines several ingredients:

- **Relying on many NTP servers**
  - ➢ Generates a large server pool (hundreds) per client
    - ➢ E.g., by repeatedly resolving NTP pool hostnames and storing returned IPs
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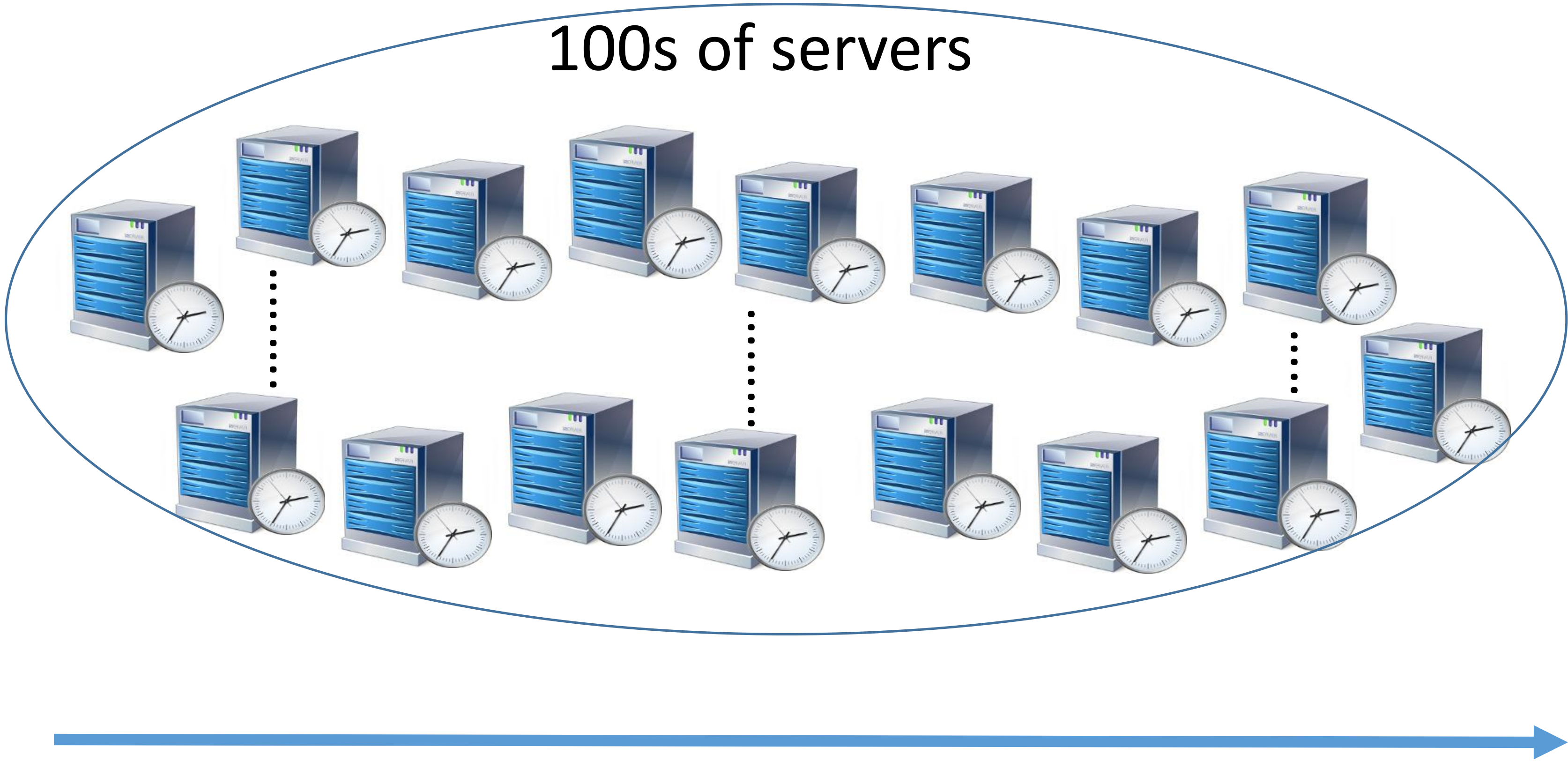
- **Smart filtering**
  - ➢ Removes outliers via a technique used in approximate agreement algorithms
  - ➢ Limits the MitM attacker's ability to contaminate the chosen time samples

Chronos' Time-Update Algorithm: Informal

- Query m (10s of) servers **<u>at random</u>**



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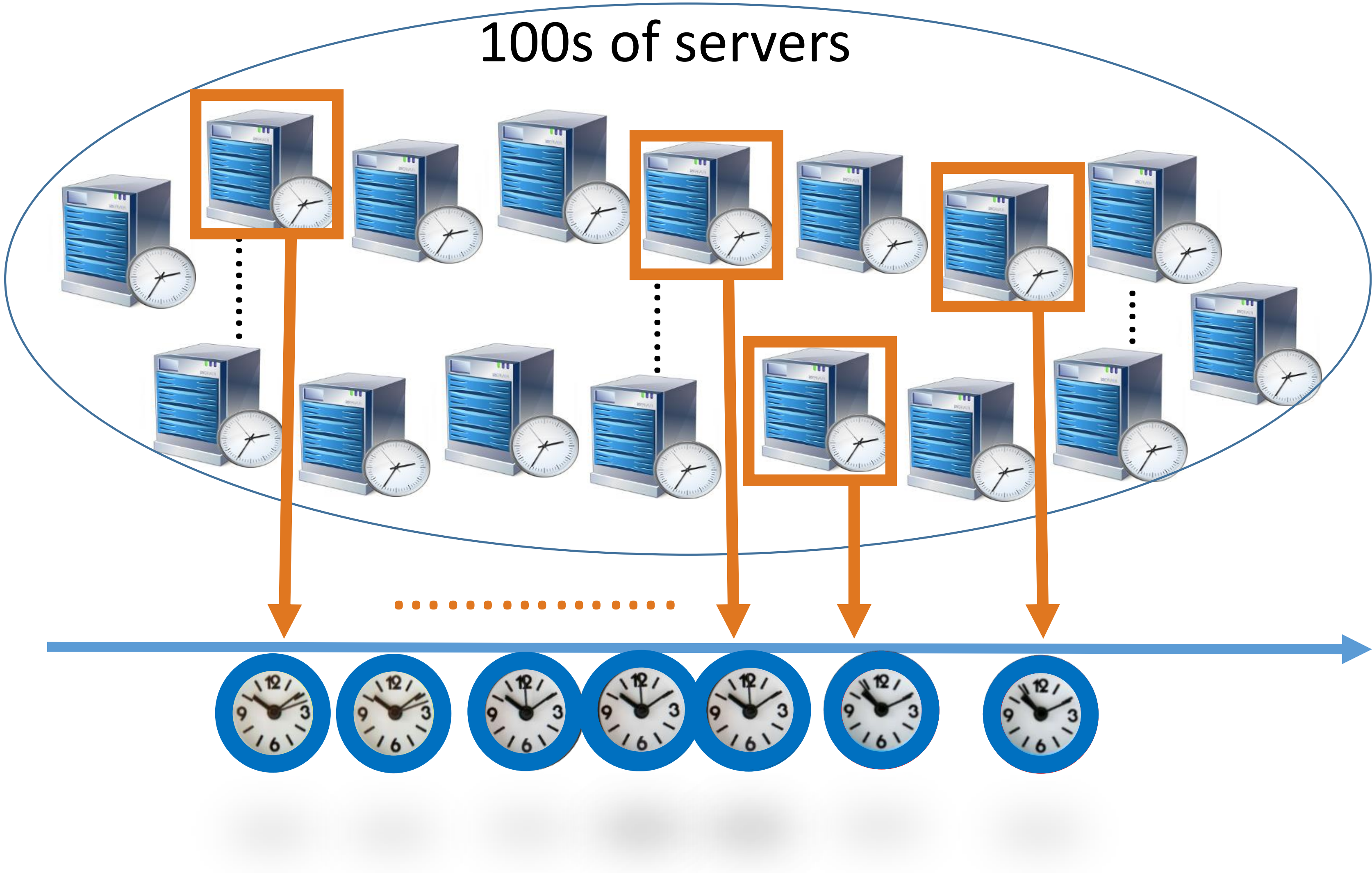

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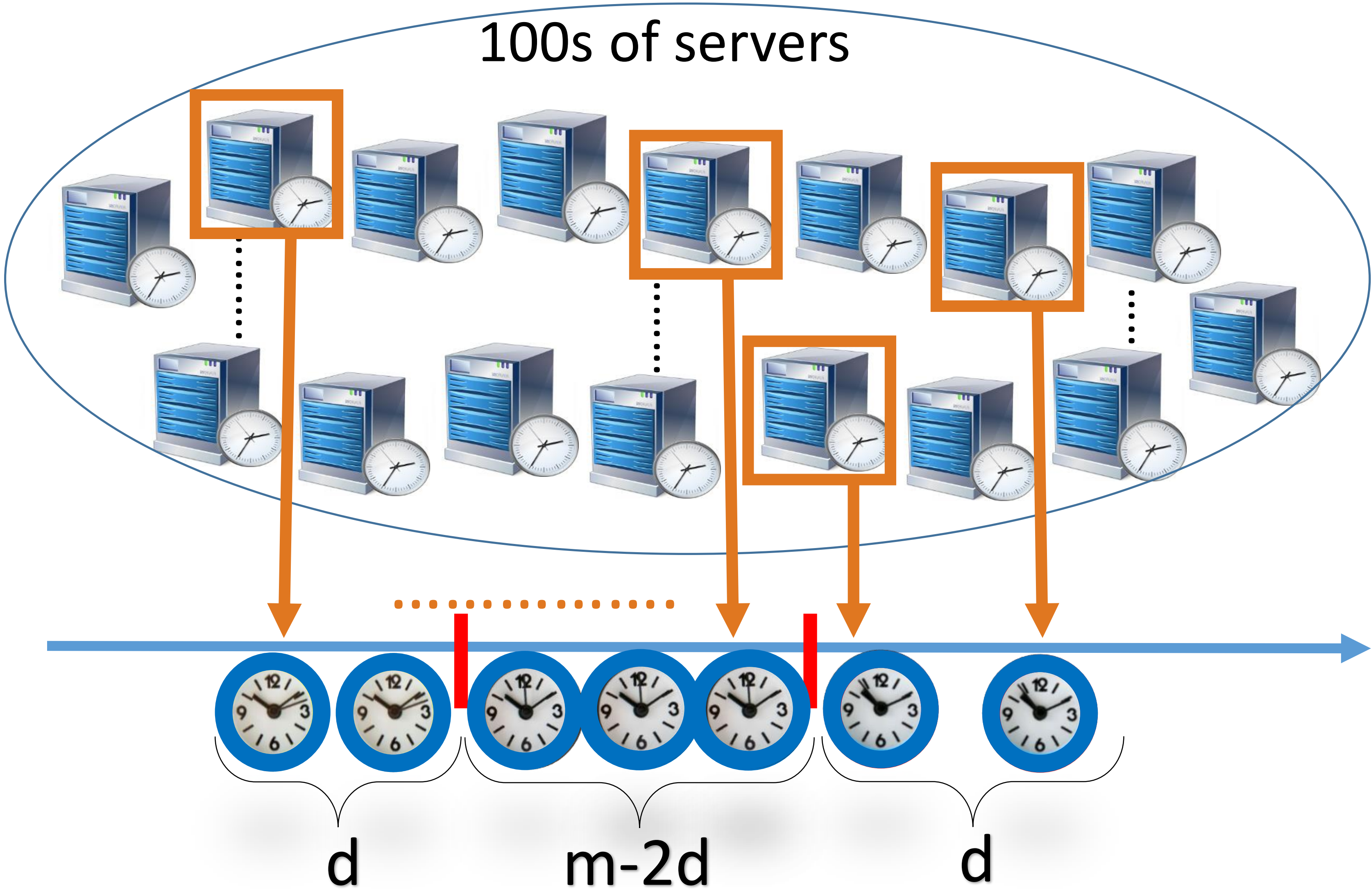

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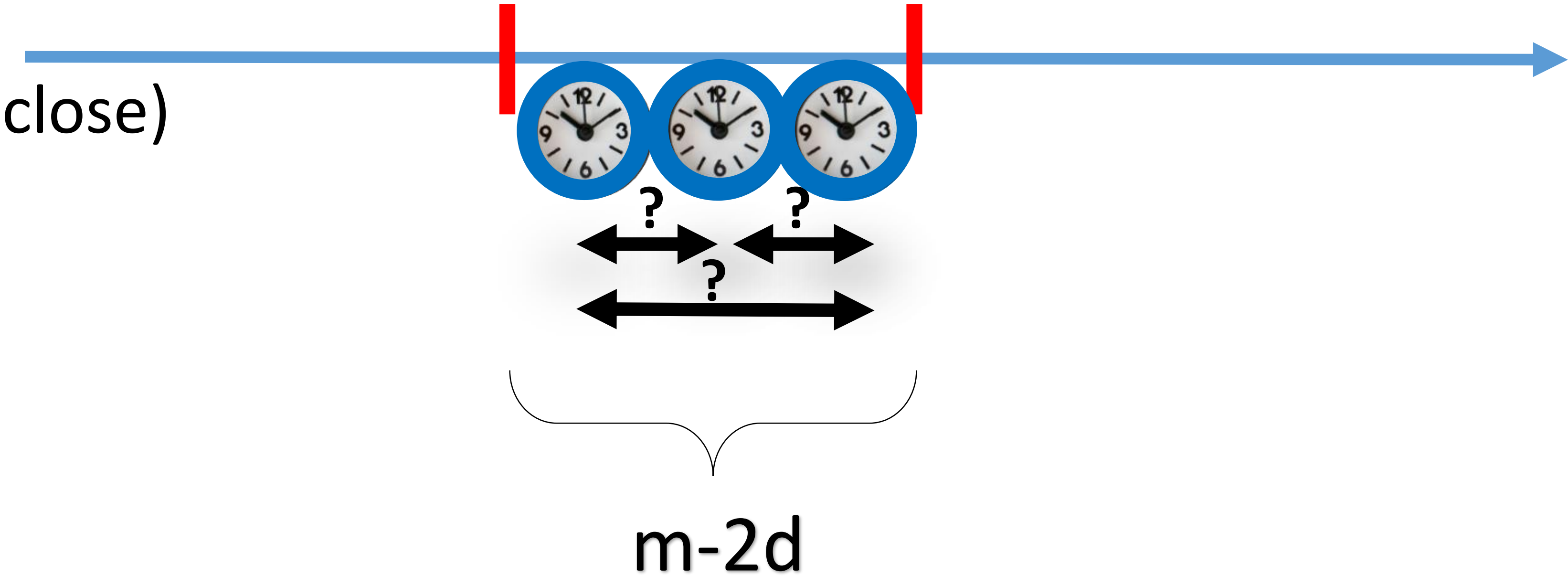
If (the remaining samples are close)



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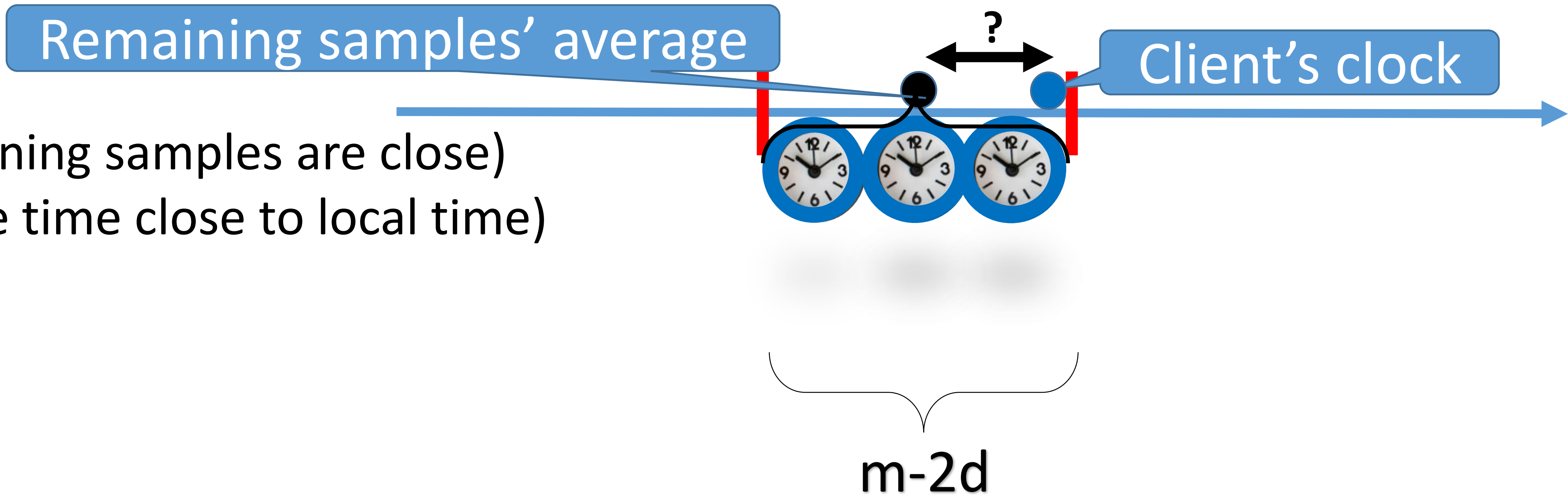

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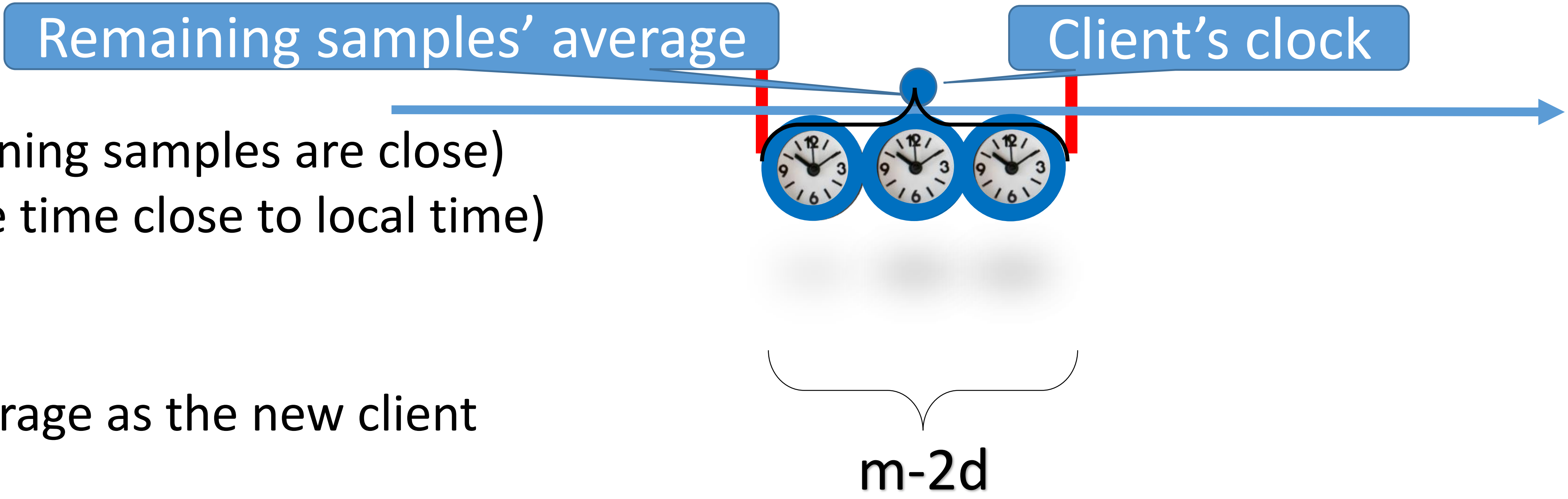

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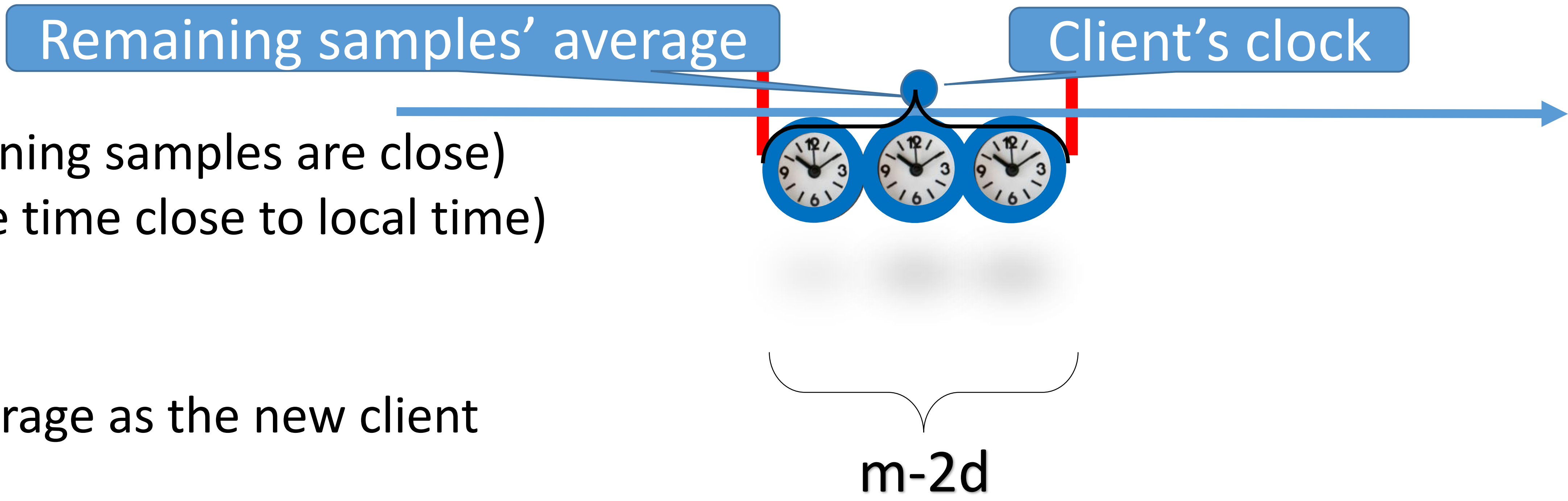

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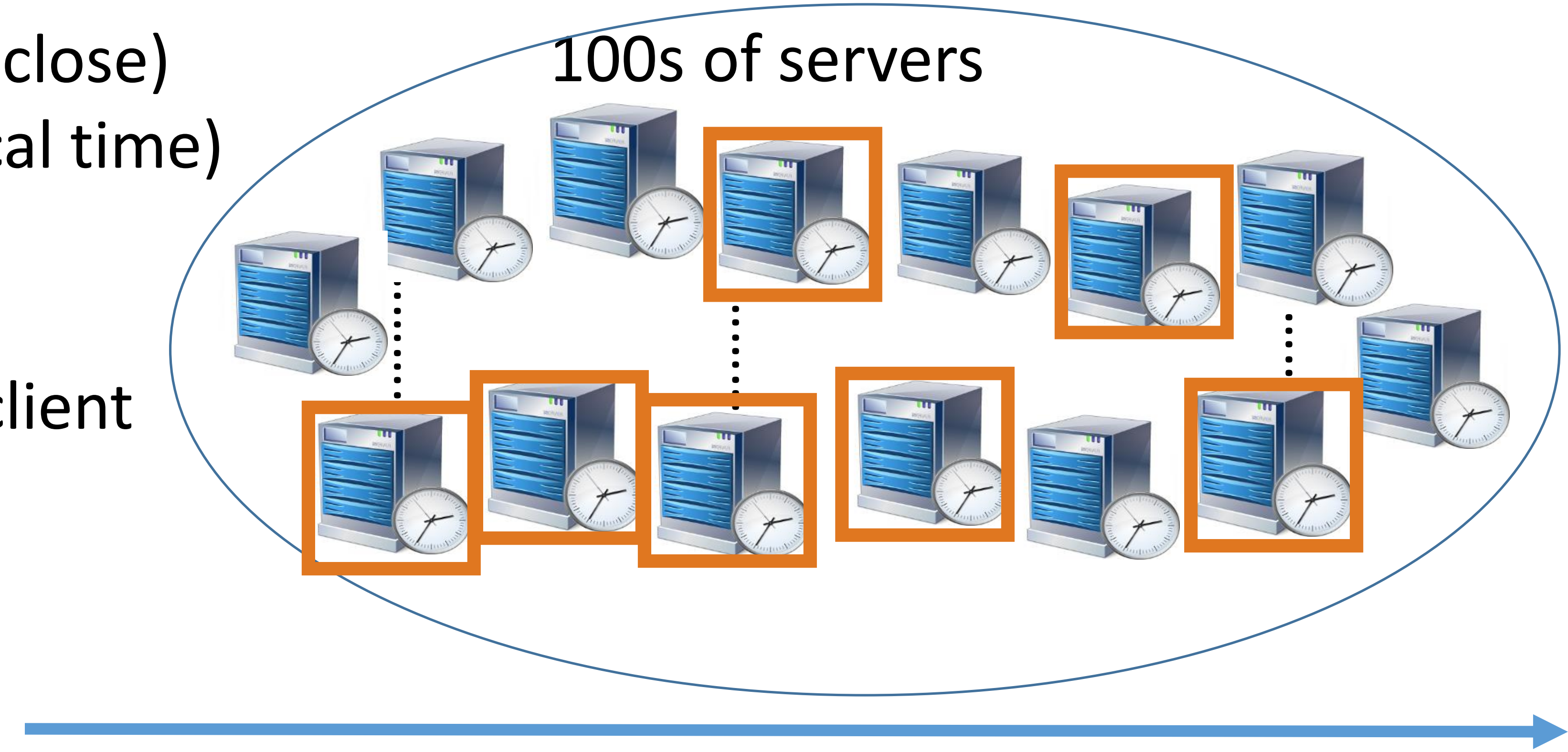

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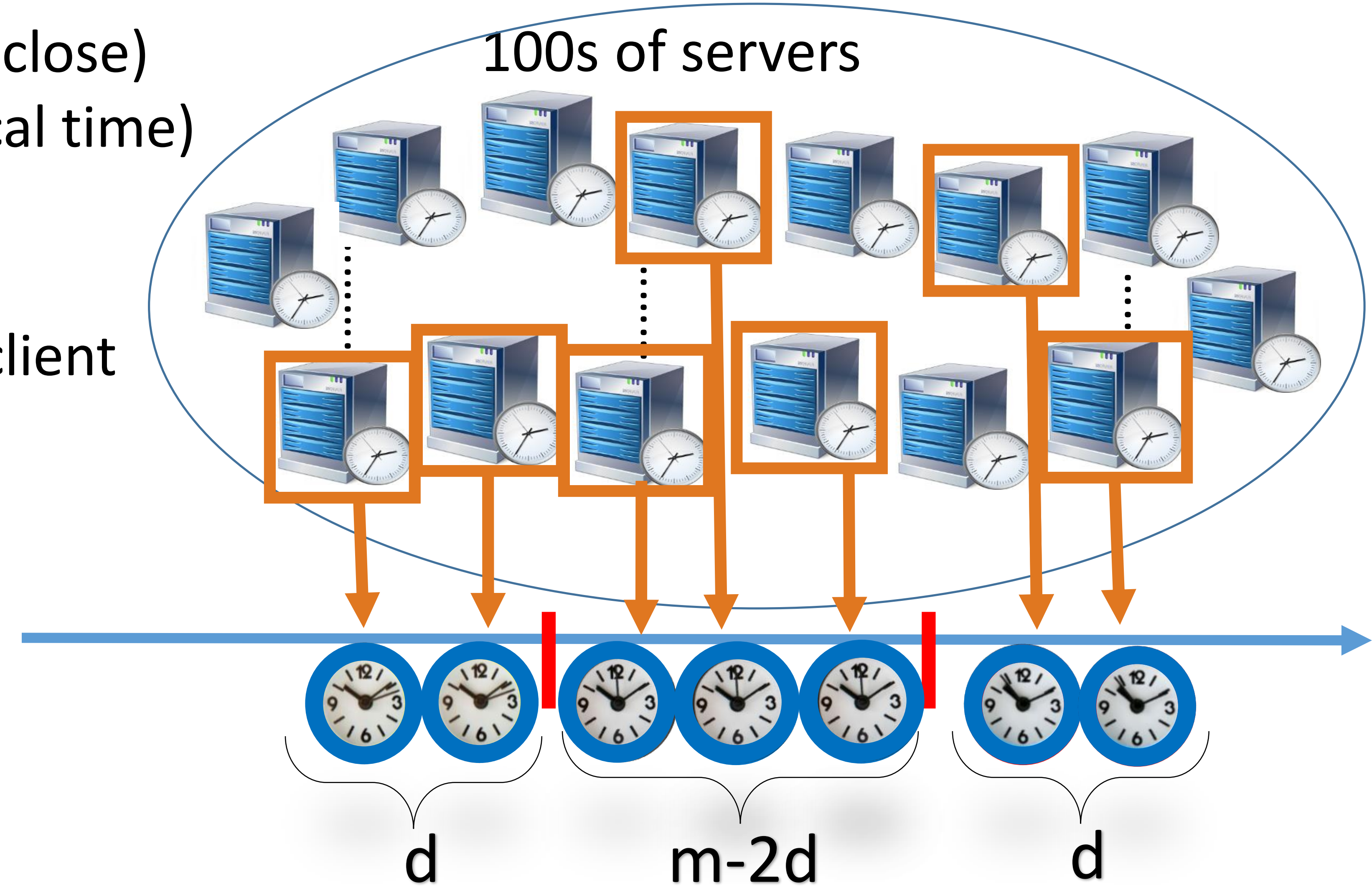

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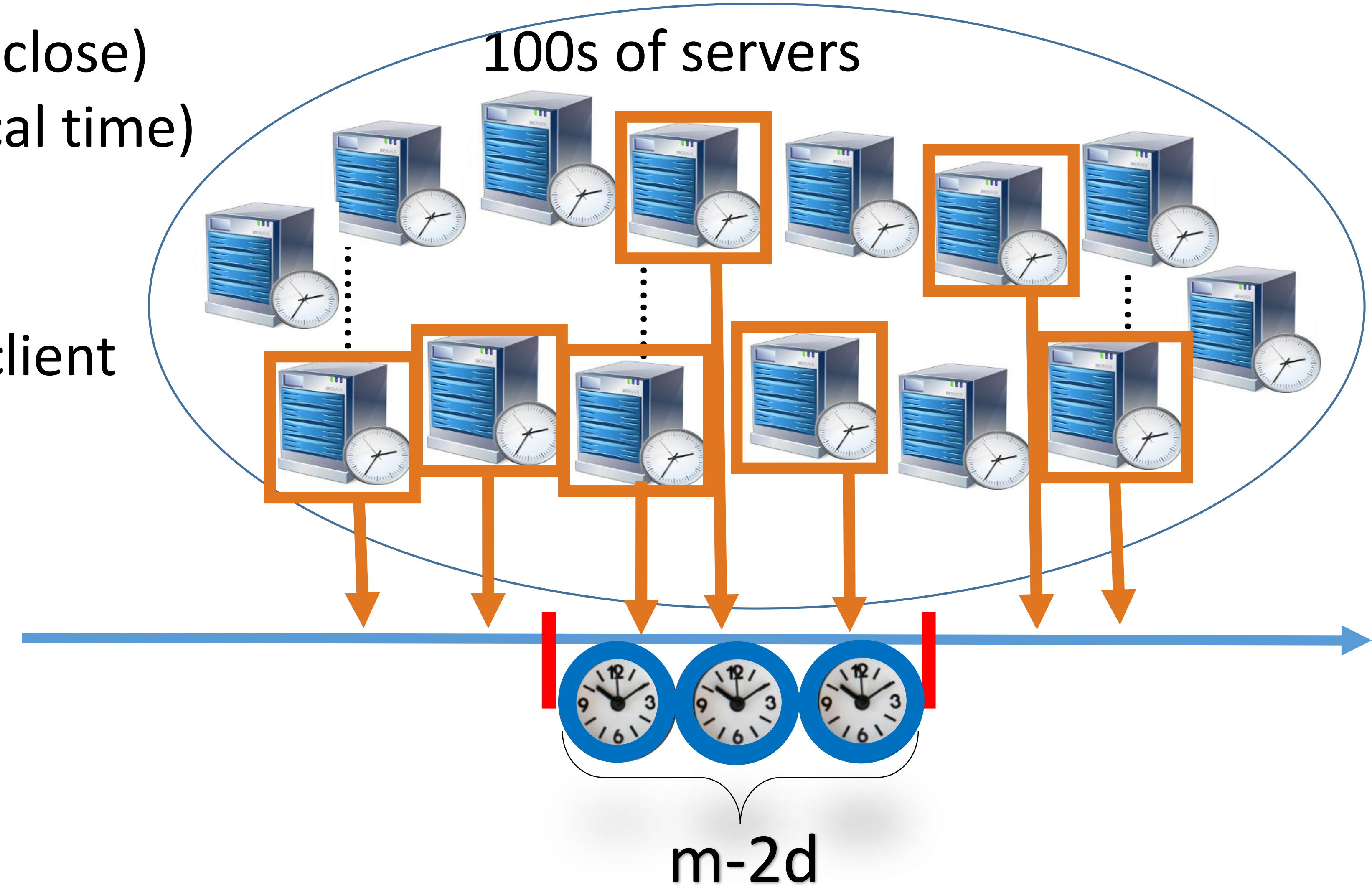

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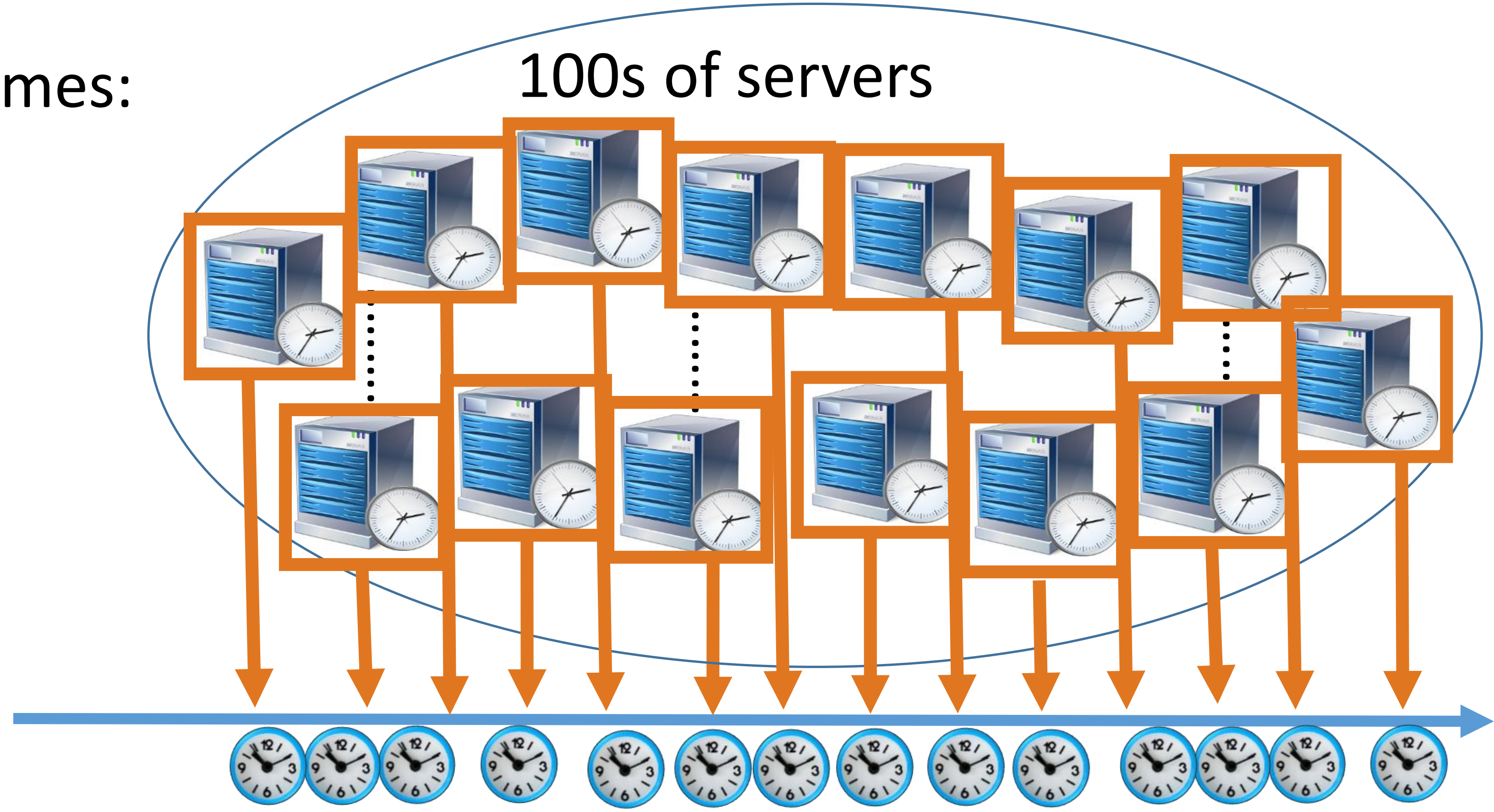

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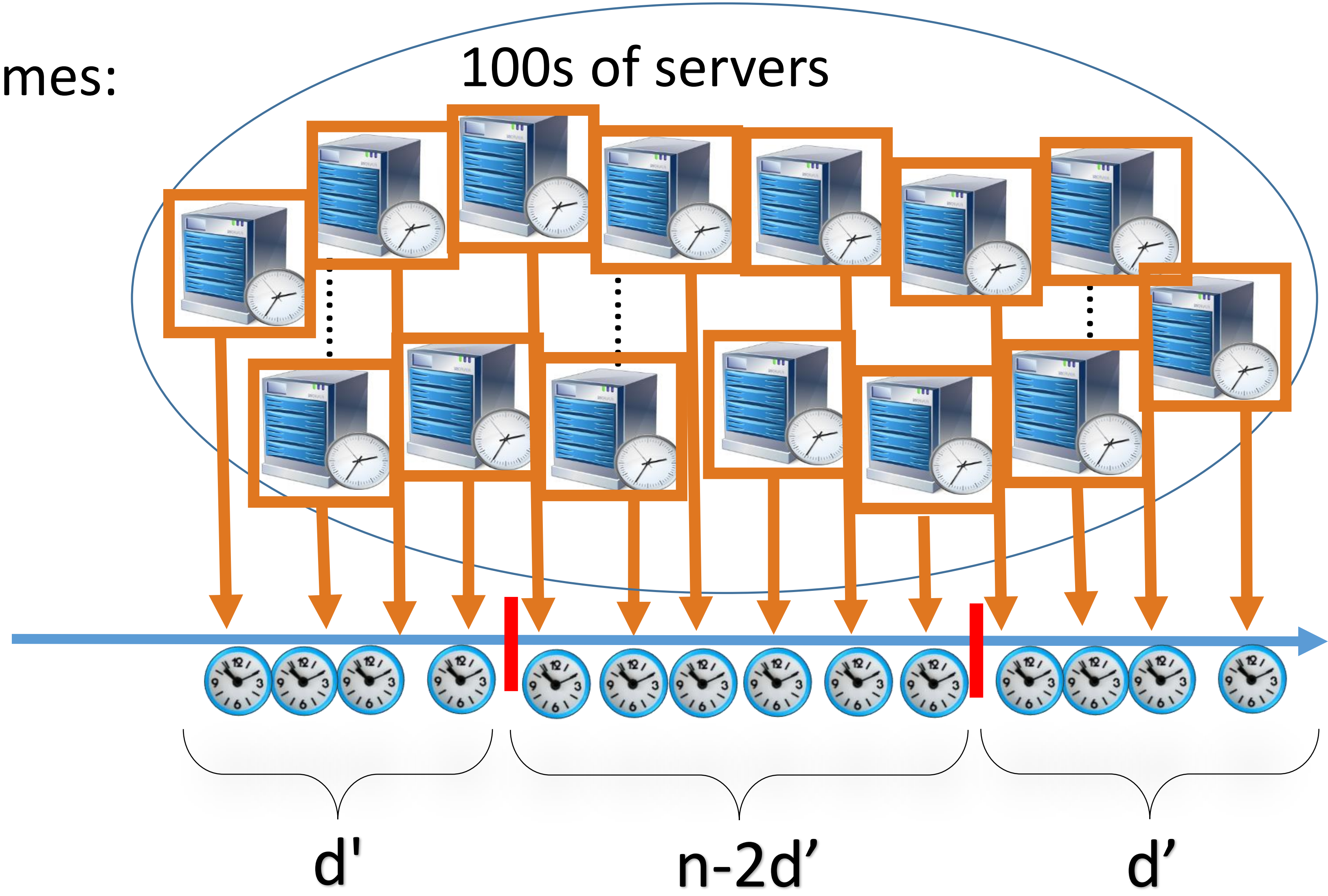

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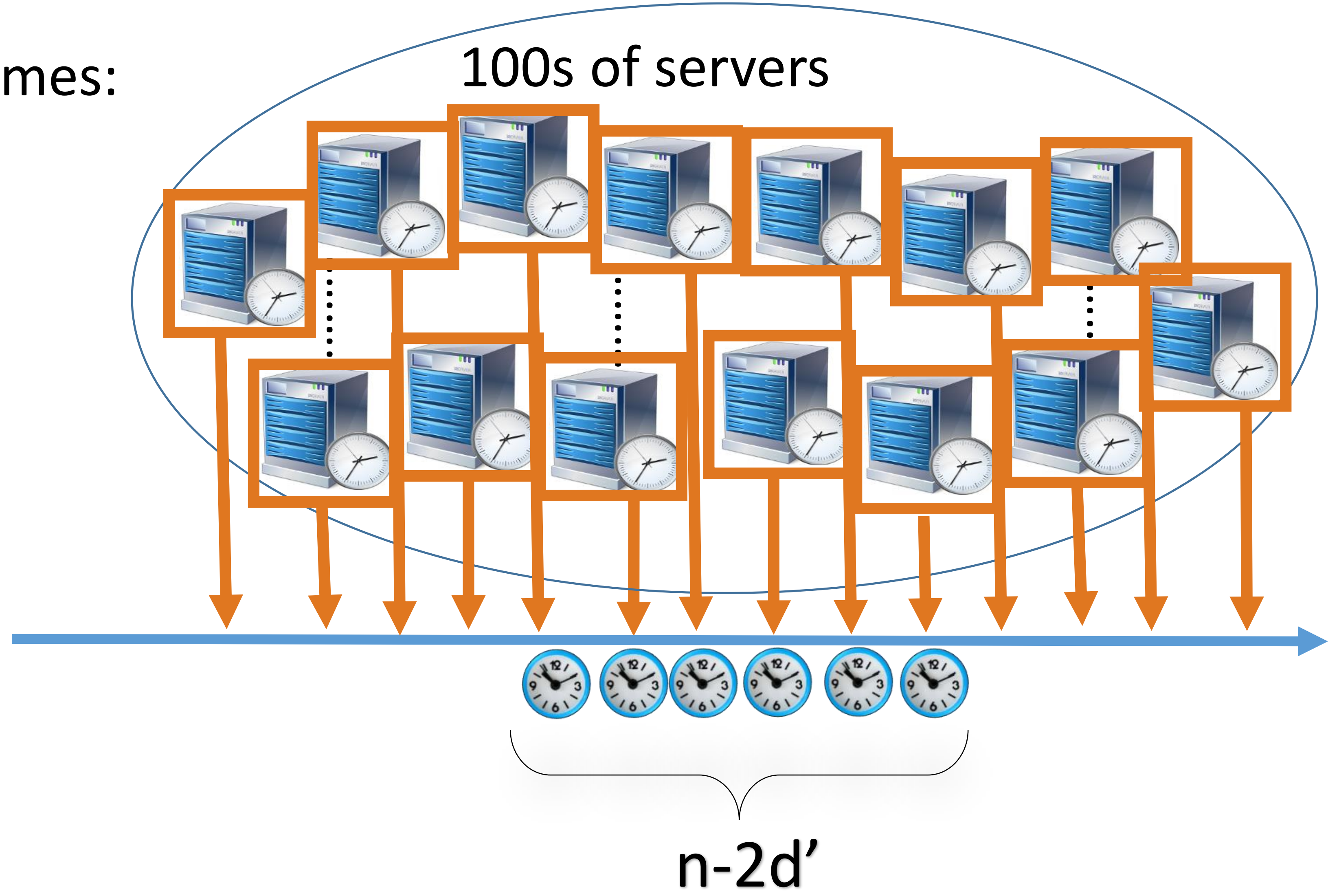

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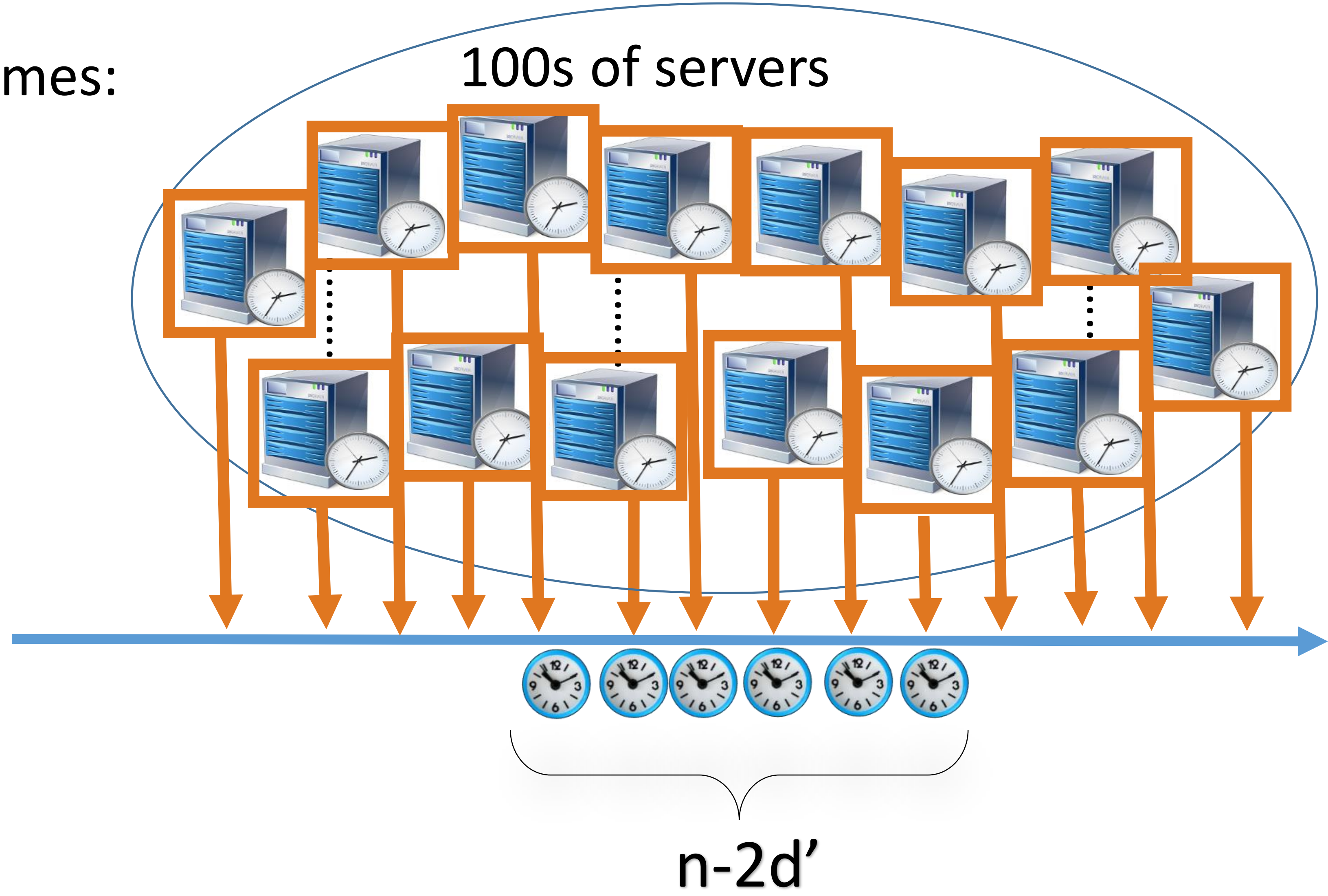

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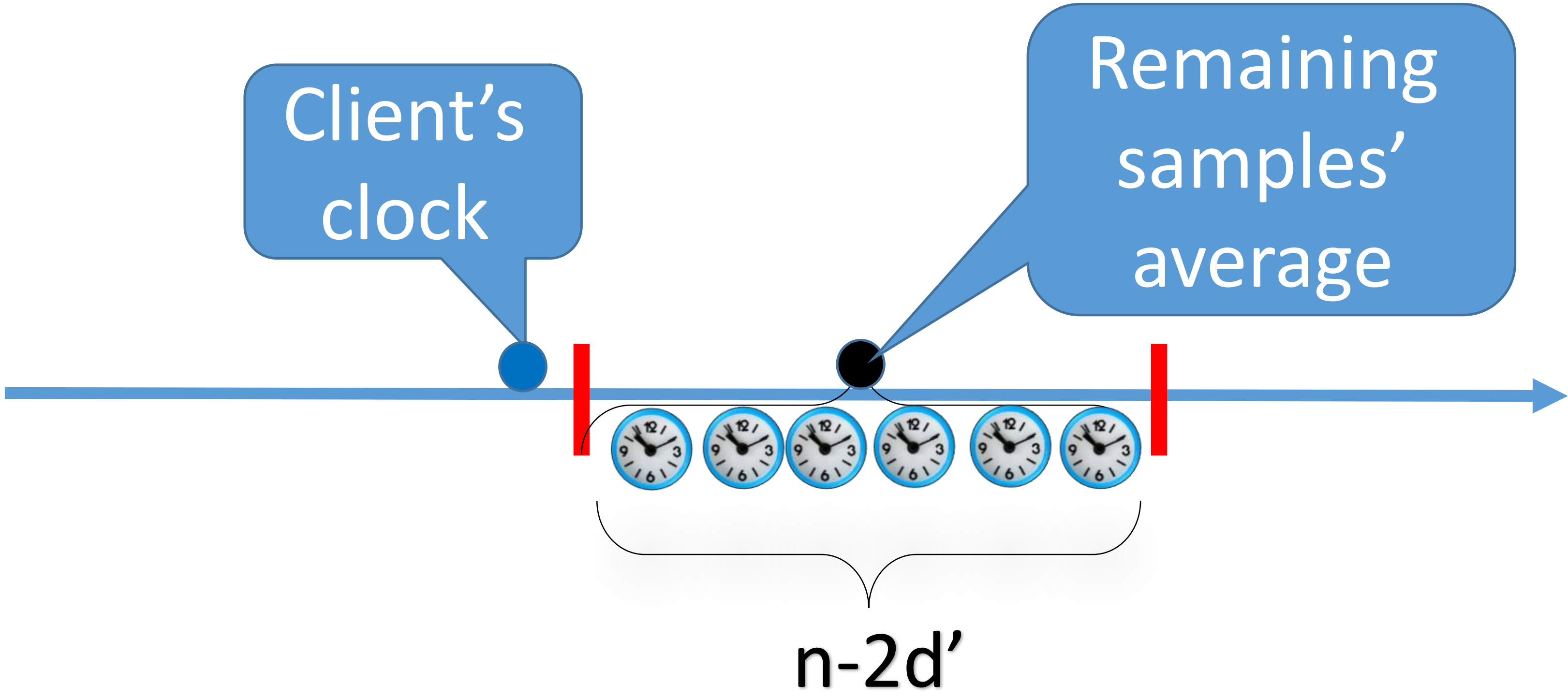

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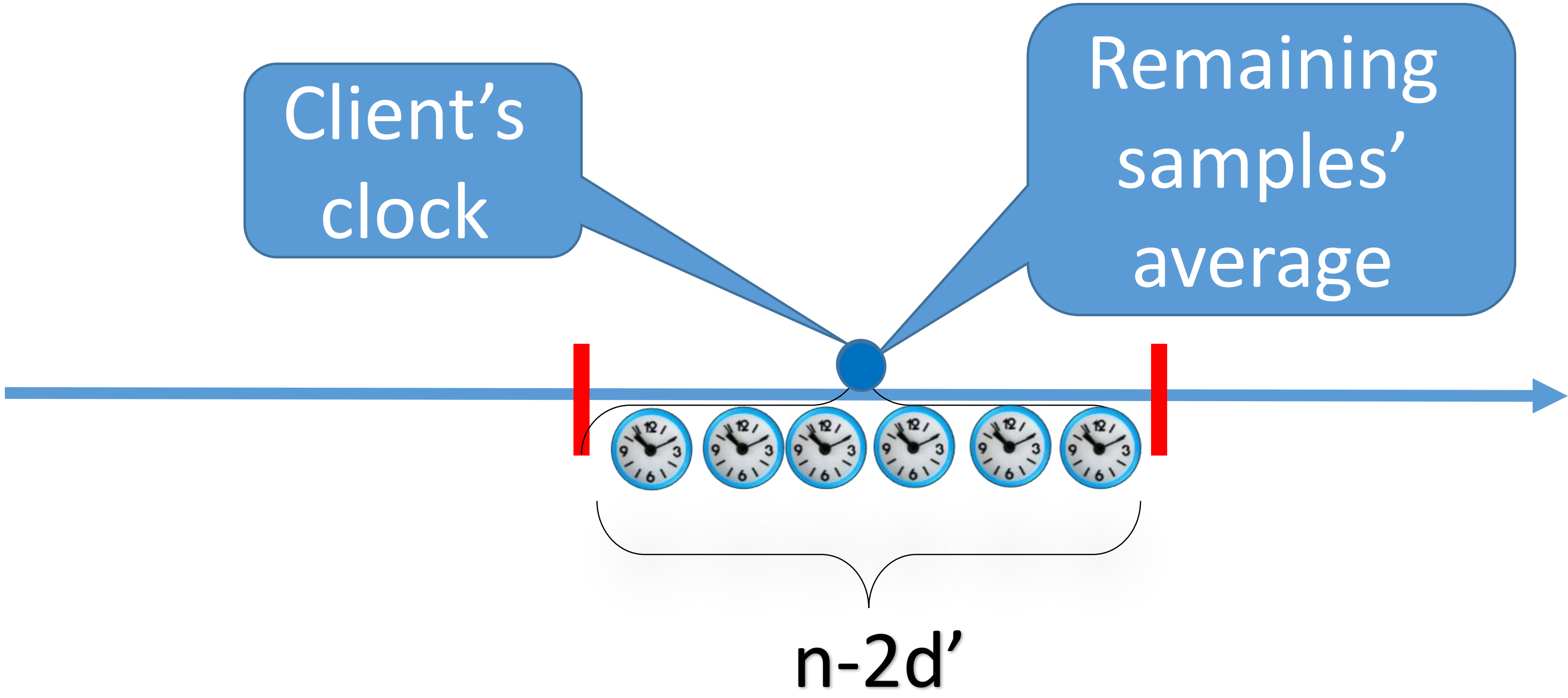


Security Guarantees

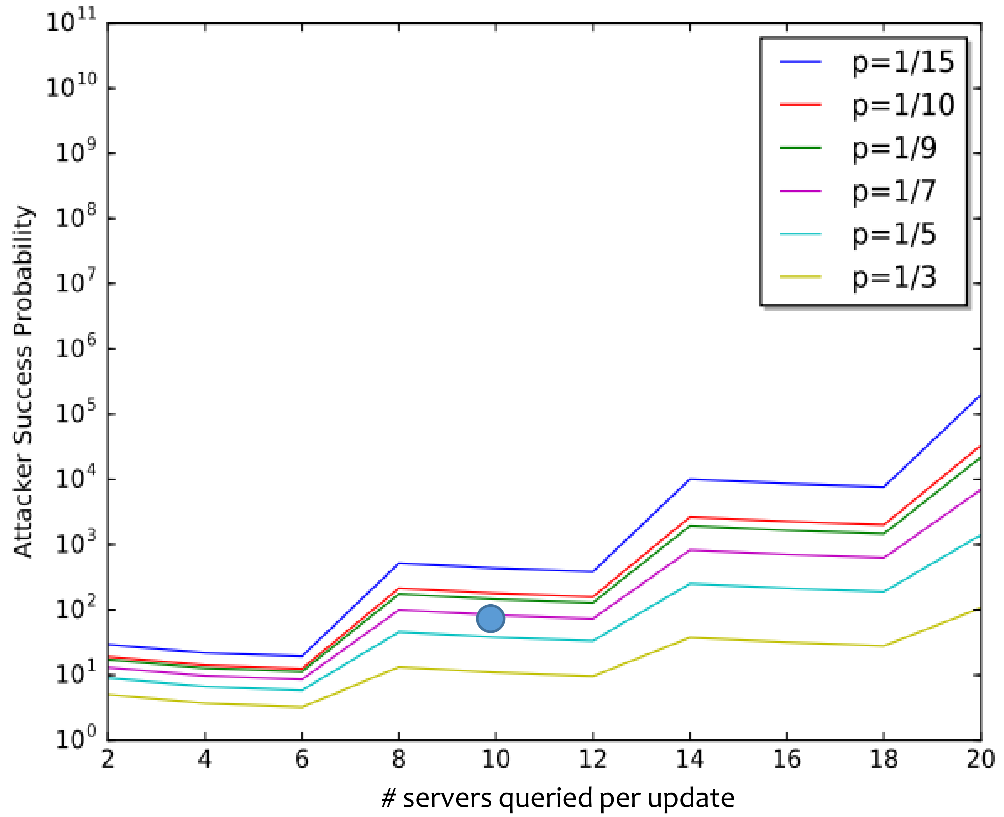
Shifting time at a Chronos client by at least **100ms** from the UTC will take the attacker at least **22 years** in expectation

- … when considering the following parameters:
  - Server pool of 500 servers, of whom 1/7 are controlled by an attacker
  - 15 servers queried once an hour
  - Good samples are within 25ms from UTC (ω=25)

- These parameters are derived from experiments we performed on AWS servers in Europe and the US

Chronos vs. Current NTP Clients

- Consider a pool of 500 servers, a p-fraction of which is controlled by an attacker.
- We compute the attacker's probability of successfully shifting the client's clock
  - ➢ for traditional NTP client
  - ➢ for Chronos NTP client
- We plot the ratio between these probabilities



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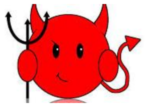
Scenario 1: #() > d #() < m-d

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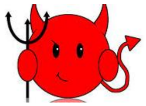
Scenario 1: #() > d #() < m-d

- **<u>Option I</u>**: Only malicious samples remain
  - ➢ <u>Assumption</u>: every good sample at most ω-far from UTC
  - ➢ At least one good sample on each side
    - → All remaining samples are between two good samples
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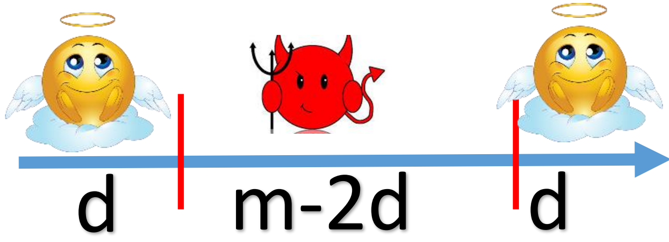

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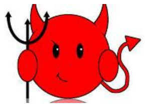
Scenario 1: #() > d #() < m-d

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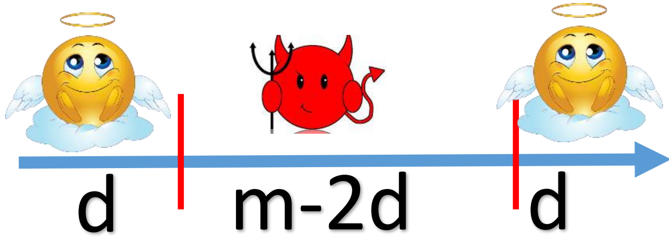

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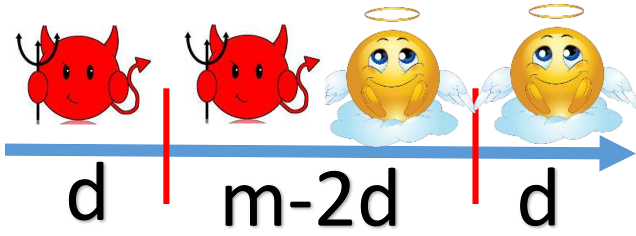

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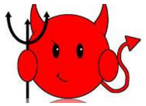
Scenario 1: #() > d #() < m-d

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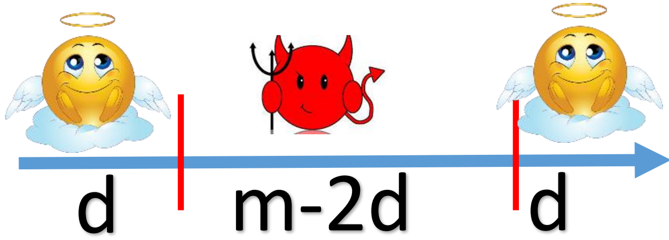

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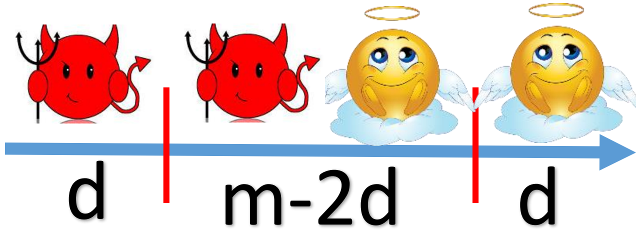

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Hence, these attack strategies are ineffective

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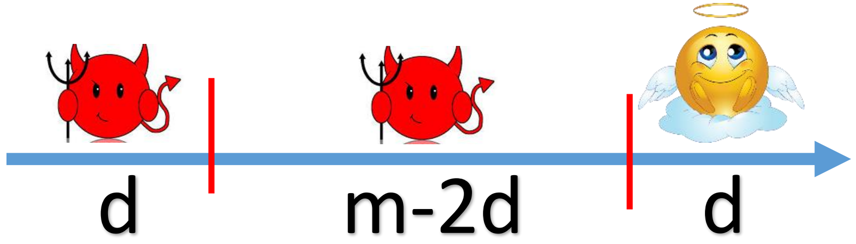

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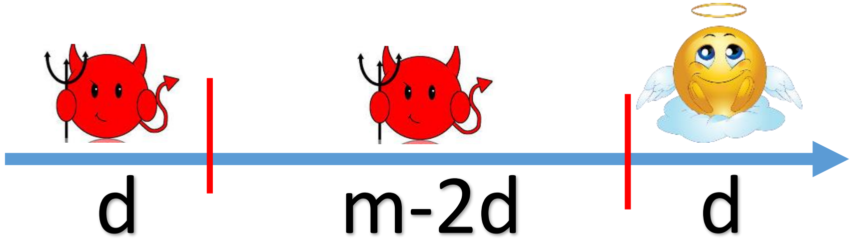

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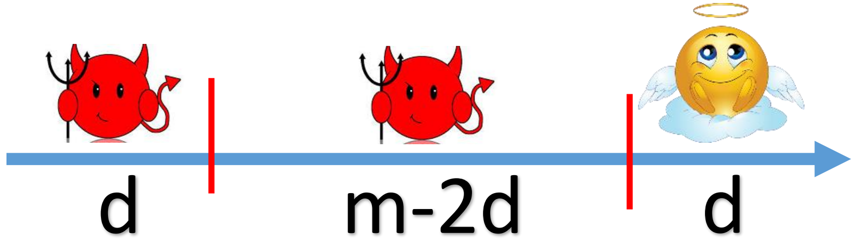

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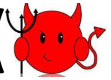
- **The probability that #()≥m-d is extremely low** (see paper for detailed analysis)
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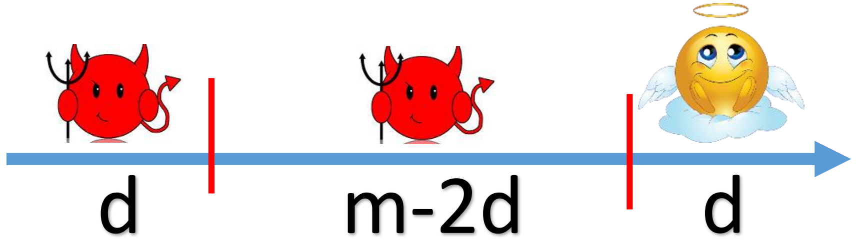

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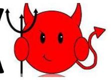
- **The probability that #()≥m-d is extremely low** (see paper for detailed analysis)
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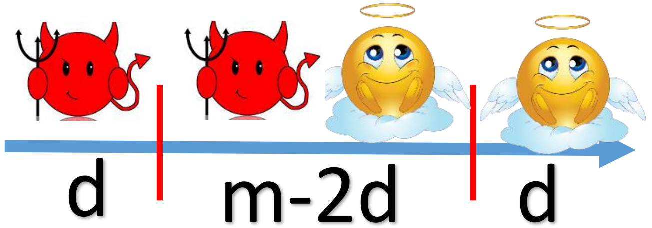
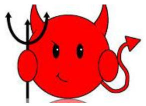
Consequently, a significant time shift is practically infeasible

Can Chronos be exploited for DoS attacks?

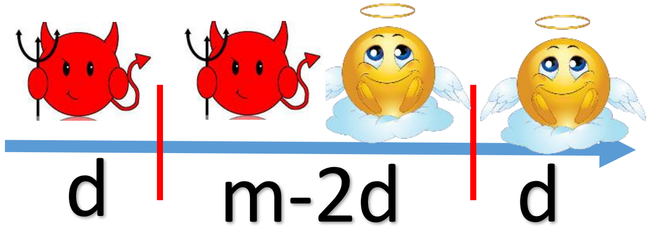
- Chronos repeatedly enters Panic Mode.

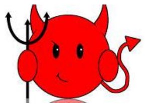


- Optimal attack strategy requires that attacker repeatedly succeed in accomplishing #() > d #() < m-d
  - At least one malicious sample remain
  - Malicious sample violates condition that all remaining samples be clustered
  - This leads to resampling (until Panic Threshold is exceeded).

Can Chronos be exploited for DoS attacks?

- Chronos repeatedly enters Panic Mode.



- <u>Optimal attack strategy</u> requires that attacker repeatedly succeed in accomplishing #() > d #() < m-d
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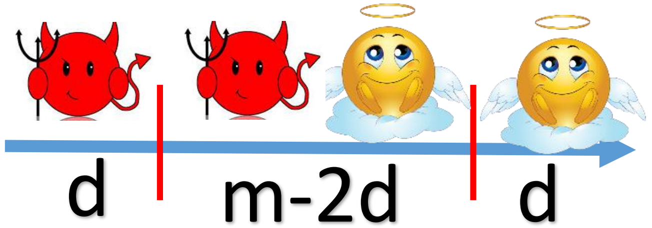
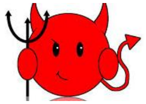


- Optimal attack strategy requires that attacker repeatedly succeed in accomplishing #() > d #() < m-d
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Even for low Panic Threshold (k=3), probability of success is negligible (will take attacker decades to force Panic Mode)

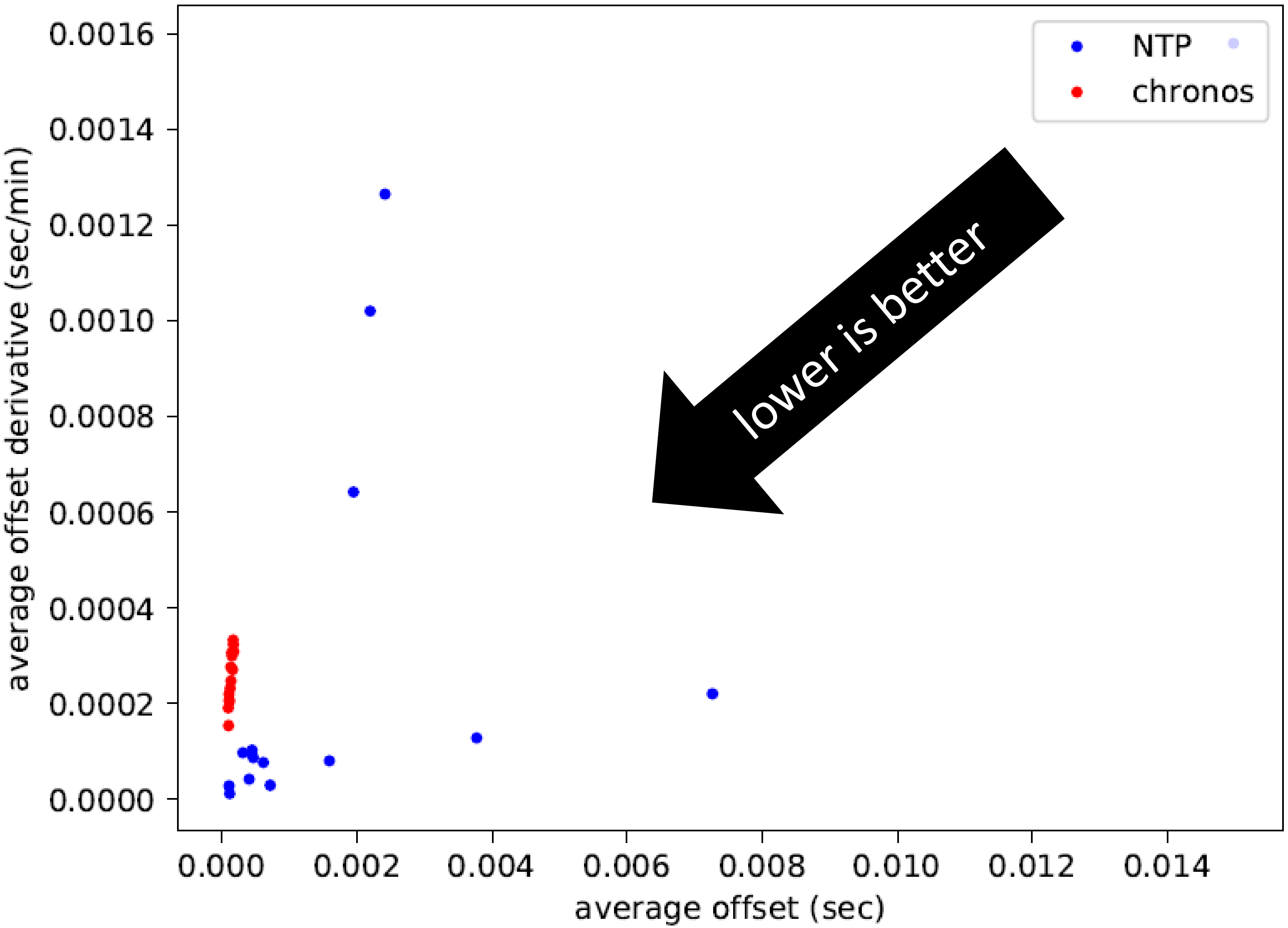
Chronos *vs.* NTPd

- Greater variety of sampled servers over time
- Provable security guarantees
- Avoids (NTPv4) source quality filters
- Possible adverse effects on precision and accuracy.

Chronos' Precision and Accuracy

- To improve precision without sacrificing security, we introduce a smoothing mechanism:
  - Return the minimal sampled offset unless its distance from the average is higher than a predefined value
- We evaluated Chronos at multiple locations in Europe and the US

Average offsets and derivatives



Conclusion

- NTP is highly vulnerable to time-shifting attacks
  - Attacker in control of a few servers/sessions can shift client’s time
- We presented the **Chronos NTP client**
  - provable security
  - backwards-compatibility
  - low overhead
- Chronos’ precision and offsets are close to NTP (around 2ms apart)

Ongoing and Future Efforts

- Evaluate Chronos at scale (security, precision, accuracy, overhead, …)
- Standardize Chronos!
- Extending Chronos to address several attack strategies
- Extensions to other time-synchronization protocols (e.g., PTP)?

Thank You

See full paper (@NDSS'18):
http://wp.internetsociety.org/ndss/wp-content/uploads/sites/25/2018/02/ndss2018_02A-2_Deutsch_paper.pdf

See last IETF draft version:
https://tools.ietf.org/html/draft-schiff-ntp-chronos-02