# Intrusion-Tolerant Parsimonious State Machine Replication

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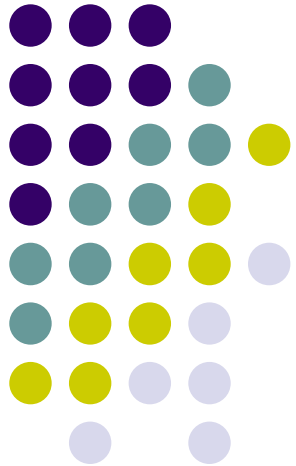
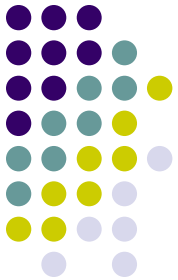


# Intrusion Tolerance (IT)



Reality

- Systems will have vulnerabilities
- Subset of vulnerabilities will be exploited eventually

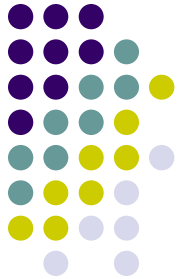
Goals

- Provide acceptable service despite intrusions
- Survivability in the face of attacks

Defense-in-depth

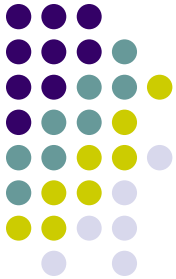
- Intrusion prevention
- Intrusion tolerance
- Intrusion detection
- Isolation & rejuvenation

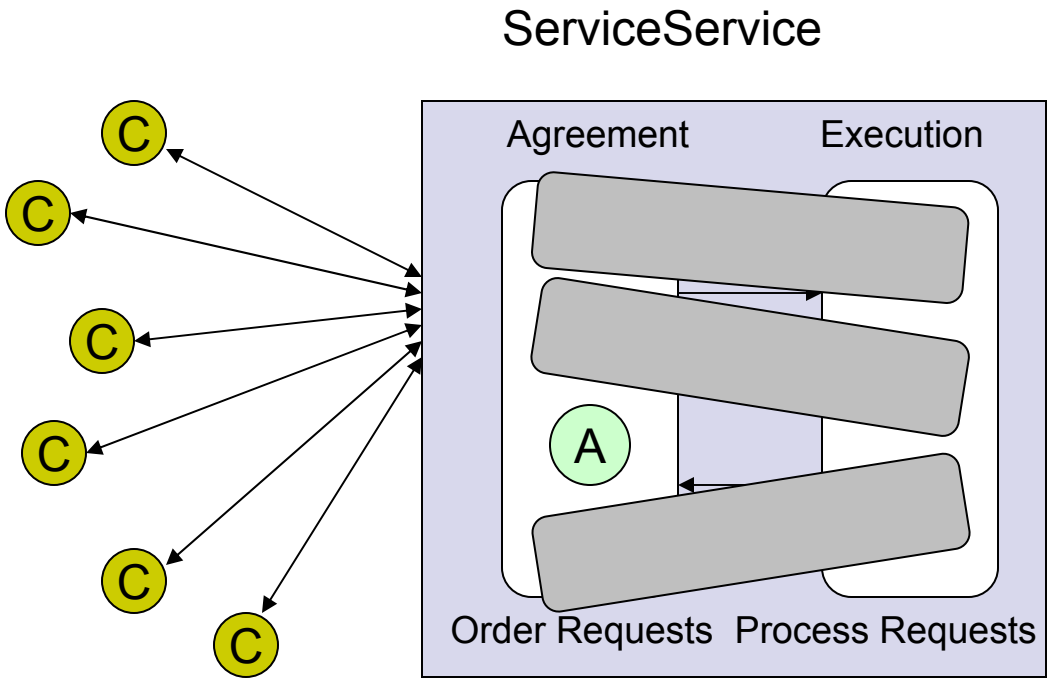
# Byzantine Fault Tolerant (BFT) Replication Protocols



- One of the potential building blocks for IT
- Caveat
  - Replicas shouldn't fall prey to same attacks
    - Diversity (N-version programming, OS heterogeneity..)
- Two categories
  - Quorum Replication (Malkhi, Reiter)
  - State-machine replication (our focus)

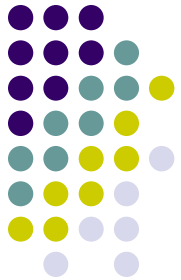
# Byzantine Fault Tolerant (BFT) State Machine Replication (SMR)





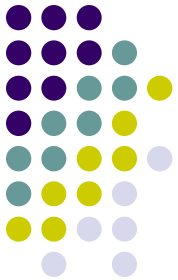

Yin et. al [SOSP'03]

# Related Work



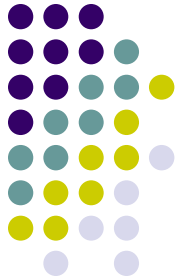
- Long line of work on BFT
- Focus of recent work
  - Making BFT practical and relevant to *real* services
  - e.g., Rampart, Fleet, SecureRing, PBFT, COCA, SINTRA, Yin et al., etc.
- Our work: similar focus, but different means
  - Focus: BFT SMR efficient, relevant to *real* services
  - Means: Efficient BFT SMR execution phase

# Parsimonious Execution



- Execution phase
  - Likely to be expensive, perhaps more than agreement
  - Often overlooked: agreement is the *harder* problem
  - Quite application dependent
- Goal
  - Improve efficiency in execution phase
  - Mechanism used must be applicable for many applications
- Key Idea – Parsimony
  - Use only a primary committee to actually execute requests
  - Reconfiguration, if committee seems to be not doing job properly
    - All replicas become temporarily active
    - Reselect primary committee

# Parsimonious Execution

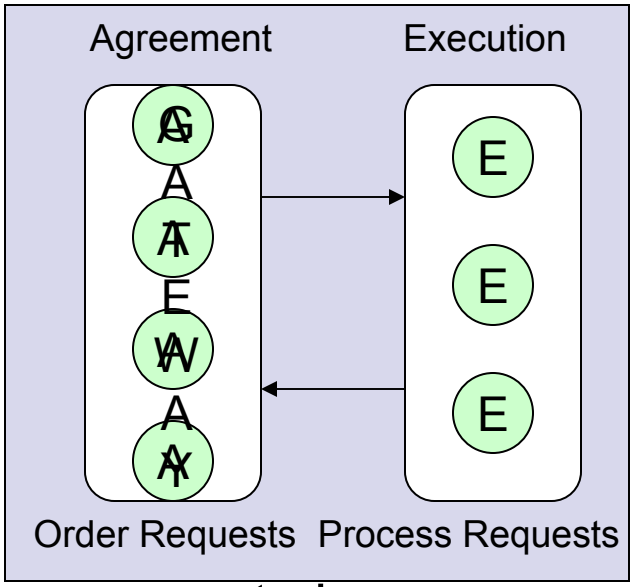


- Premise: Faults are exception rather than norm
- Fault-free-runs overhead
  - Minimize redundant processing & computation
- Faulty runs overhead
  - May be temporarily higher, but not unacceptable
- Uses timing assumptions not for safety/liveness, but for efficiency

# Outline

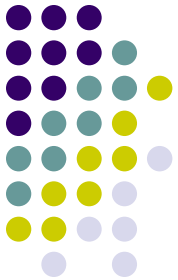
- System Model
- Base Protocol
  - Fault-free operation
  - Reconfiguration
  - Analysis
  - Properties
- Lazy Updates
- MAC-Extended Protocol
- Ongoing work, Conclusion

# Gateway



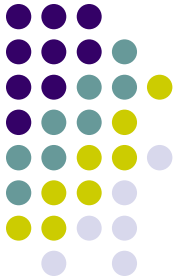

- Logical substitute for agreement phase
- Serializing mechanism
  - Orders client requests
  - Sends requests in same order to all execution replicas
- Trusted
  - Made trustworthy by distributed implementation (agreement replicas) using atomic broadcast protocol (e.g., PBFT)
- Not aware and doesn't care about the primary committee

# System Model



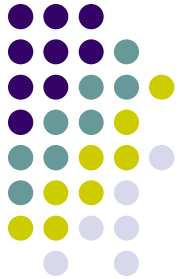
- Asynchronous processing & communication
- Gateway and a set *S* of *n* execution replicas
  - $n \geq 2t+1$ :– total # execution replicas
  - *t* :– max # replicas simultaneously faulty
  - $t+1$ :- size of primary committee
- FIFO, quasi-reliable channels
- Public-key cryptography + MACs
- Computationally bounded adversary

# Notations



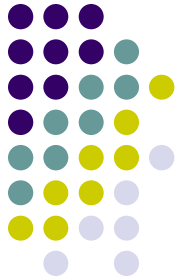
- *(t+1)-subset* :- subset of *S*; exactly *t+1* replicas
- *PC* :- Ordered list, contains all *(t+1)-subsets* that could be primary committees (identical and constant across all replicas)
  - e.g., Set of all possible (*t+1*)-subsets of *S*
- $c_i$ :- committee number at replica *i*
  - Initialized to 1, at all replicas
- $P_i$ :- primary committee at replica *i*
  - $P_i$ is the $c_i^{th}$ element of *PC*
- $OFL_i$ :- omission fault list at replica *i*
- $CFL_i$ :- commission fault list at replica *i*

# Base Protocol



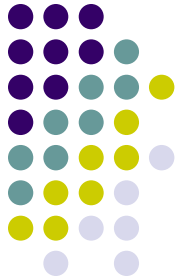
- Signed msg exchanges among replicas
- Gateway sends request (say seq# *x*) to all replicas
- Each committee member **execute request, monitor progress**
  - Executes request; determines result *r* & update *u*
  - Sends reply msg (with *r*) to gateway
  - Sends reply-update msg (with *r*, *u*) to all replicas
  - Starts timer, expects other committee members to send reply-update message before timeout
- Each Backup **monitor progress**
  - Starts timer, expects committee members to send reply-update message before timeout

# Base Protocol: Fault-free operation



- Gateway
  - receives t+1 replies with identical *r* values
  - accepts *r* as result for request *x*
- Replicas
  - receive t+1 reply-updates with identical *r,u* values
  - if backup, apply state update *u*
  - move request *x* from *input-queue* to *handled-queue*

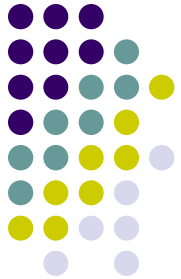
# Base Protocol: Reconfiguration



- Committee members could be corrupted/slow
- Reconfiguration
  - Needed to ensure progress
  - Must not be possible for faulty backups to initiate, when committee indeed is performing correctly
  - Initiated only with sufficient proof

    replica $i$ is added to fault-list of a correct replica →
    all correct replicas will eventually add $i$ to their fault-lists
  - Progress guarantee
    - Gateway WILL accept response for request($x$) at end of reconfiguration

# Base Protocol: Reconfiguration Triggers (1/2)



if reply-update from committee member $i$ not received in time
send suspect-omission($i$)

if badly formatted but correctly signed msg $m$ received from $i$
send suspect-commission(type-1, $i$, $m$)

if reply-updates with differing $r$,$u$ values received from ≥2 committee members
send suspect-commission(type-2, $I$, $\Psi$)

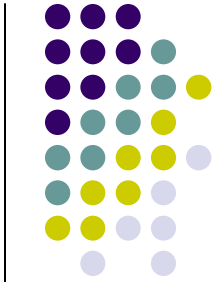
I = set of those replicas

$\Psi$ = set of their different reply-update messages

if any replica $i$ had sent reply-update with wrong $r$ or $u$ value
send suspect-commission(type-3, i, proof)

Proof = $i$'s reply-update msg & $t+1$ correct reply-update msgs

# Base Protocol: Reconfiguration Triggers (2/2)



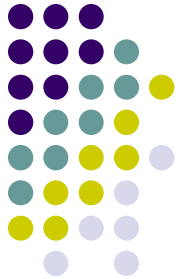
*received suspect-omission (i) from k for request x*
  if reply-update (*i*, *x*) received
    forward reply-update (*i*, *x*) to *k*
  if suspect-omission (*i*) received from *n-t* replicas
    add *i* to OFL
    if (*i* is committee member)
      reconfiguration ()

*received suspect-commission(type-1, i, m)*
  add *i* to CFL
  if (*i* is committee member)
    reconfiguration()

*received suspect-commission (type-3, i, proof)*
  add *i* to CFL
  if (*i* is committee member)
    reconfiguration()

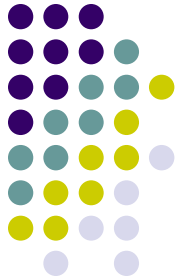
*received suspect-commission (type-2, I, proof)*
  if (all elements in set I are committee members)
    reconfiguration ()

# Base Protocol: Reconfiguration Protocol



- Step 1:
  - All replicas temporarily become active
  - New commission-faulty replicas may be identified
- Step 2:
  - Reselect new primary committee skipping over elements of *PC* containing replicas in fault-lists

# Base Protocol: Reconfiguration Protocol (Details)



$\Gamma = \{(i, \gamma) \mid (I, \Psi)\}$
$(i, \gamma)$ for each replica $i$ in OFL|CFL
$(I, \Psi)$ from type-2 suspect-commission msg

reconfiguration()
  send reselect ($j$, $c$, $\Gamma$)
  if !(executed request $x$)
    execute request $x$
    send reply-update($j$, $x$) to replicas, reply($j$, $x$) to gateway

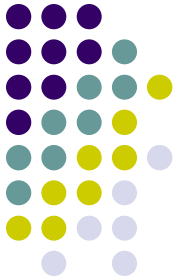
Temporary Active Phase

  if (request($x$) $\notin$ handled-set)
    wait for reply-update msgs with identical $r$,$u$ values from $t+1$ replicas
    move request($x$) to handled-set
  if any replica i had sent reply-update with wrong $r$ or $u$ value
    send suspect-commission(type-3, $j$, $i$, proof)
    add $i$ to CFL

Committee Reselection

  set $c$ to the smallest integer s.t. $c^{th}$ element of PC doesn't contain any element in OFL or CFL
  set $P$ to the $c^{th}$ element of $PC$

# Reconfiguration Protocol: Analysis

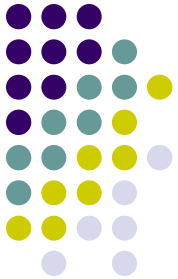


- Committees at correct replicas may temporarily differ, but will eventually concur

  replica *i* is added to fault-list of a correct replica →
  all correct replicas will eventually add *i* to their fault-lists

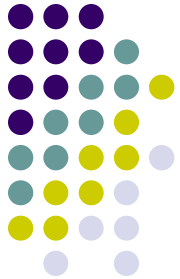
- Eventual goal of reconfiguration
  - "Settle" on an all-correct (t+1)-subset as committee
  - *O(f)*, where $f \leq t$ is #replicas in combined fault-lists of all correct replicas
  - Note: gateway doesn't have to wait till settling to accept response

# Reconfiguration Protocol: Denial-of-service attacks



- Uncorrupted replicas may be added to OFL
- *Maybe f > t*
- If |OFL ∪ CFL| > t
  - Refresh OFL entries (CFL entries – permanent)
  - Increment reconfiguration cycle
  - Committee reselection done using same rule as before
  - Suspect-omission msgs carry reconfiguration cycle
    - Valid only for that reconfiguration cycle
  - No longer *O(f)*, but progress still guaranteed
    - Subject to quasi-reliable channel assumption
    - Subject to no more than *t* replicas actually *corrupted*

# Base Protocol: Properties



Termination Gateway sends request → it eventually *accepts* response

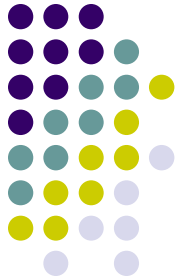
Total Order Updates for $x^{th}$ gateway request same at all correct replicas

Update Integrity Updates for $x^{th}$ gateway request happens exactly once, and only if gateway actually sent that request.

Response Integrity Response accepted by gateway → at least one correct replica sent that response

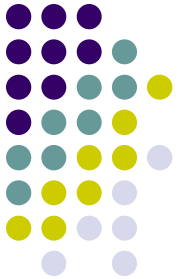
Parsimony Unless faulty behavior of some committee member has been observed by some replica in a manner that is provable to any other correct replica, gateway requests will be executed only by $t+1$ replicas constituting primary committee

# Base Protocol: Drawbacks and Extensions



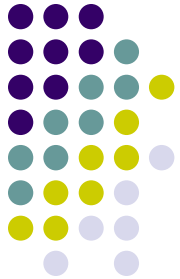
- Drawbacks
  - Backups receive reply-update msgs
  - Backups apply state updates after every request
  - Uses public-key signatures for all inter-replica messages
- Extensions
  - Lazy Updates at backups using checkpointing
  - MAC-Extended Protocol

# Checkpointing for Lazy Updates at Backups



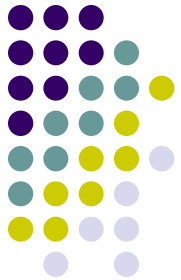
- Update backup states only when needed (reconfiguration)
- Periodic checkpoint requests
  - Processed just like a regular gateway request
  - *t+1* identical replies received → stable checkpoint
- Stable checkpoint → state update, if requested, will be eventually received
- Trade-off: Higher reconfiguration latency vs. reduced processing overhead

# MAC-Extended Protocol



- MAC-mode
  - Replicas don’t receive reply-updates from others
  - Lazy backup updates
  - Only gateway-to-replica, replica-to-gateway msgs (except for infrequent checkpoint requests)
  - As long as gateway *accepts* response in time
- Base-mode
  - Caused by gateway’s req-retransmission msg

# Conclusion



- Parsimony applied to Byzantine fault model
- Reduced overhead in fault-free case
- Additional overhead if faults in committee
  - Detection + reconfiguration latency
- Pronounced benefits expected for
  - larger group sizes
  - Computation/communication intensive apps
  - Infrequent/inexpensive/localized state updates
- Ongoing work – experimental evaluation