Towards Full-Stack Adaptivity in Transaction Management Systems deployed in Untrusted Environments

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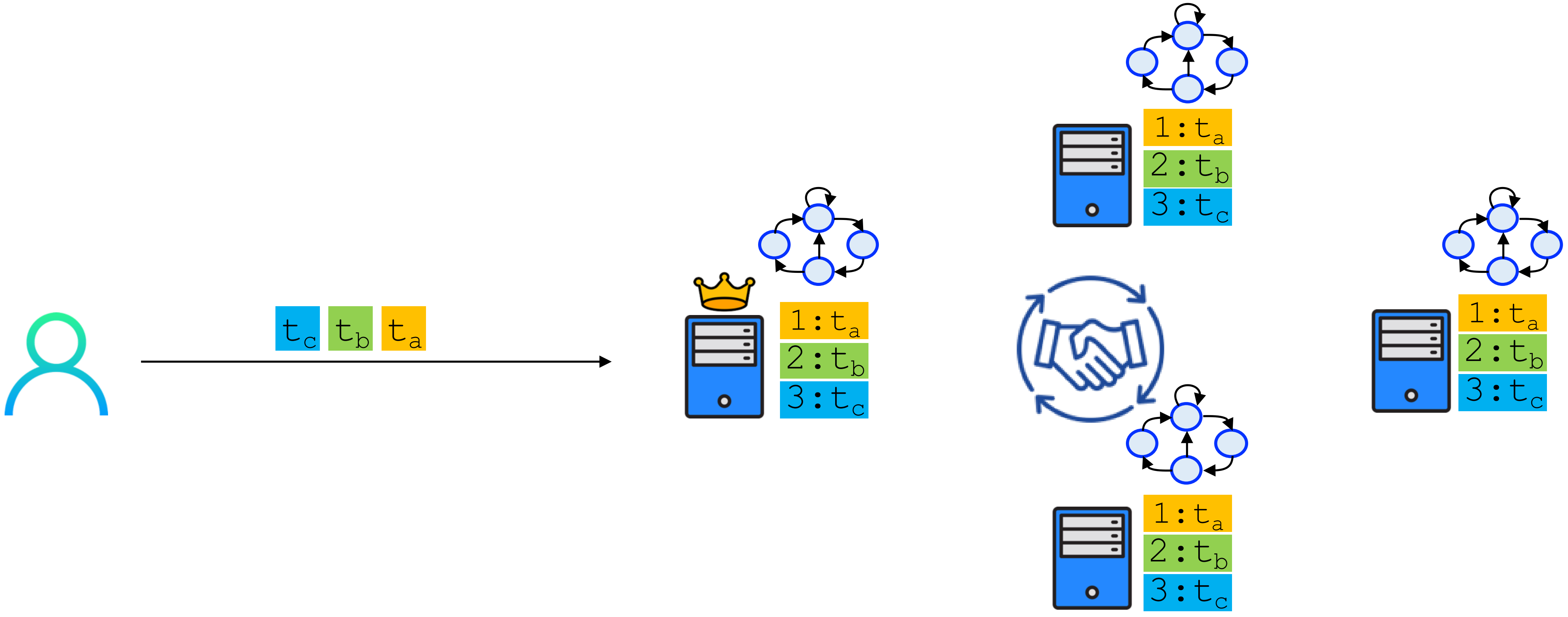
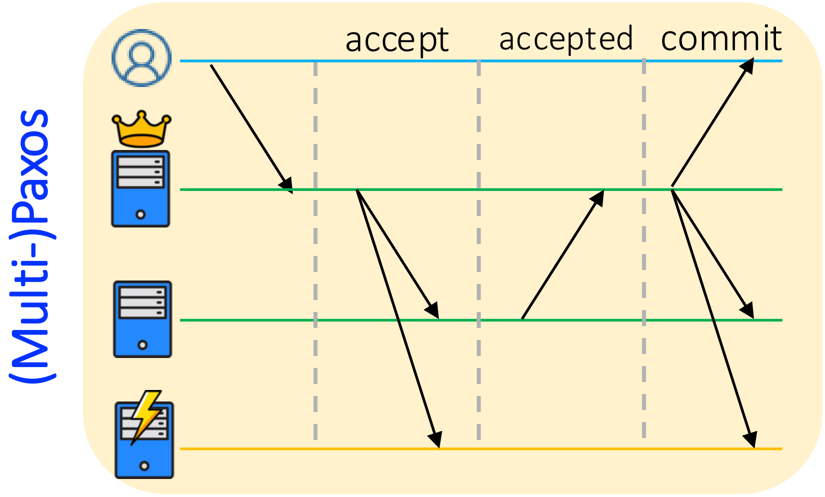
Distributed transaction processing



State Machine Replication: a replicated service whose state is mirrored across different deterministic replicas

- Assign each client request an order in the global service history and execute it in that order

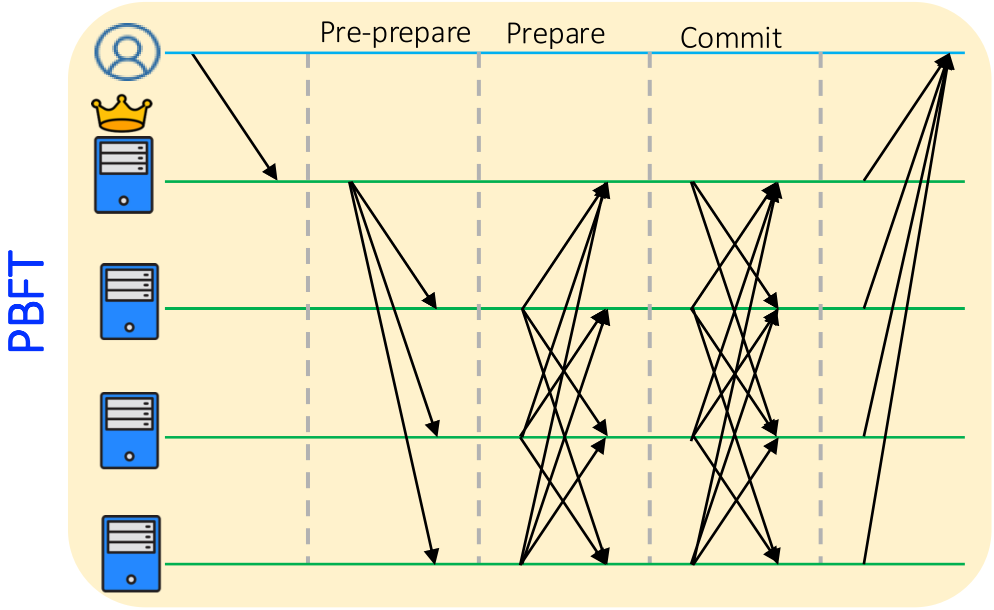
Crash fault-tolerant protocol: (Multi-)Paxos



- Requires 2f+1 nodes to be able to tolerate f parallel crash failures
- How to deal with Byzantine failure?
    - nodes exhibit arbitrary, potentially malicious, behavior
    - Potential causes: software bugs, hardware failures, malicious attacks

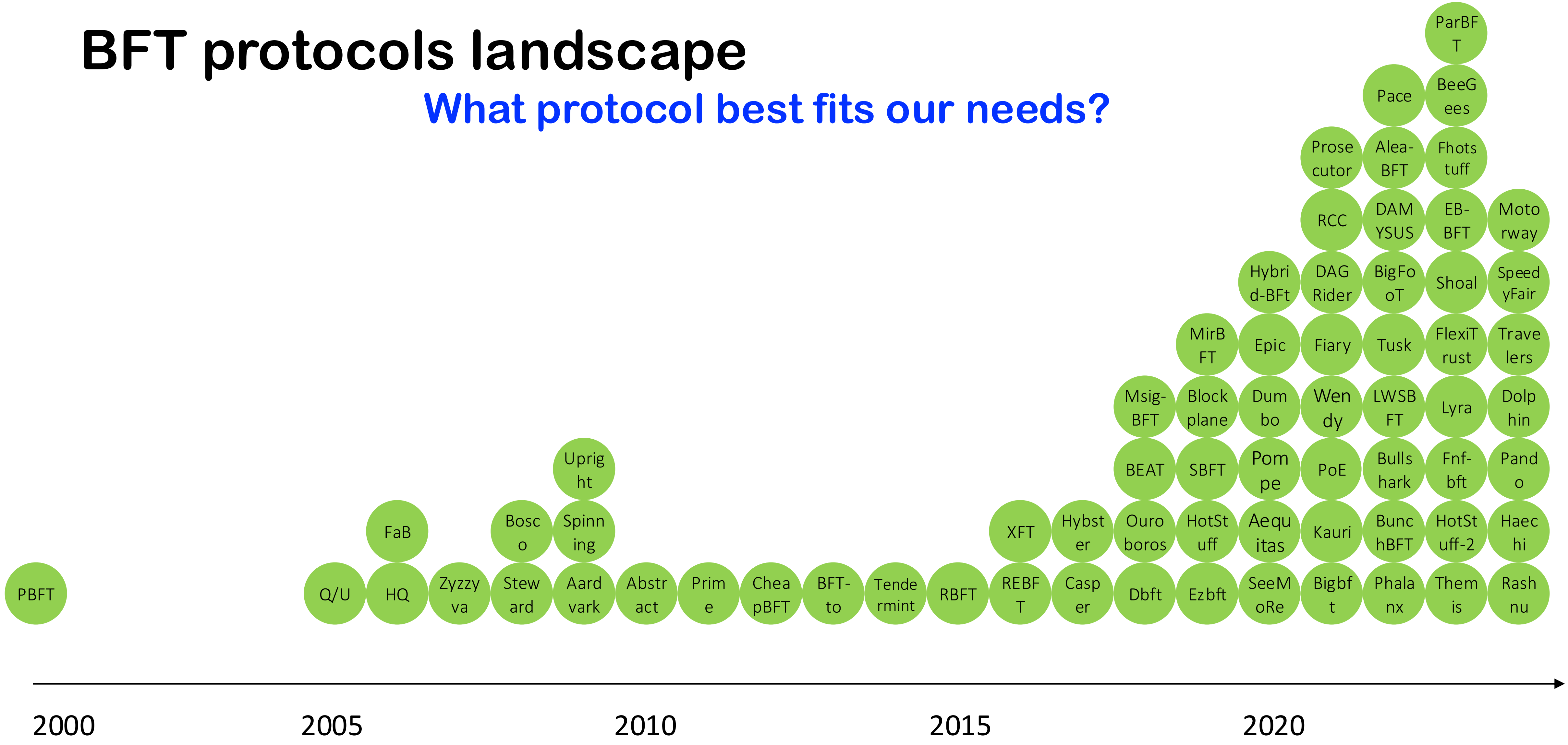
Byzantine fault-tolerant protocol: PBFT

- Nodes can fail arbitrarily, including deviating from the protocol
- Require 3f+1 nodes to tolerate f concurrent failures
- E.g., PBFT



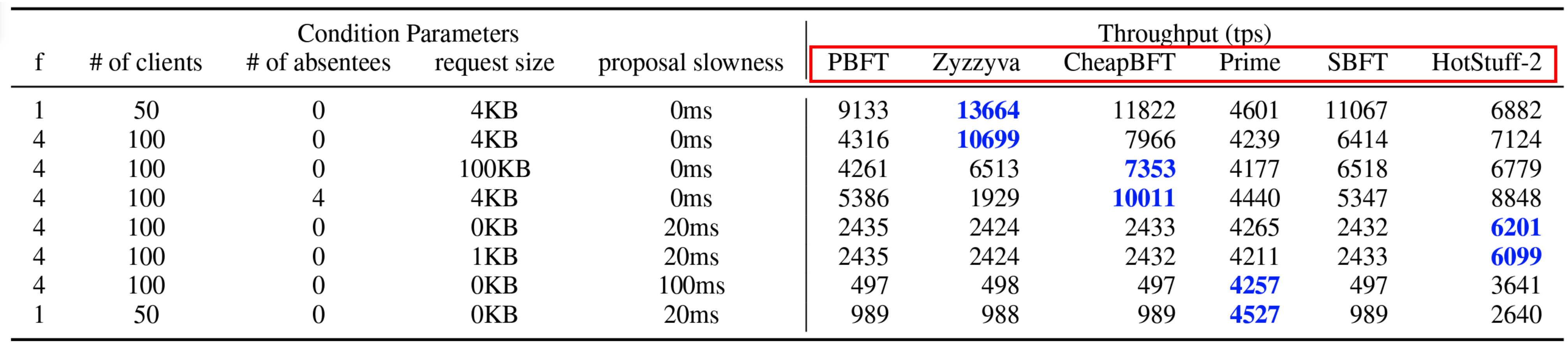
BFT protocols landscape

What protocol best fits our needs?



Challenge 1: consensus protocol

- No one-size-fits-all BFT consensus protocol

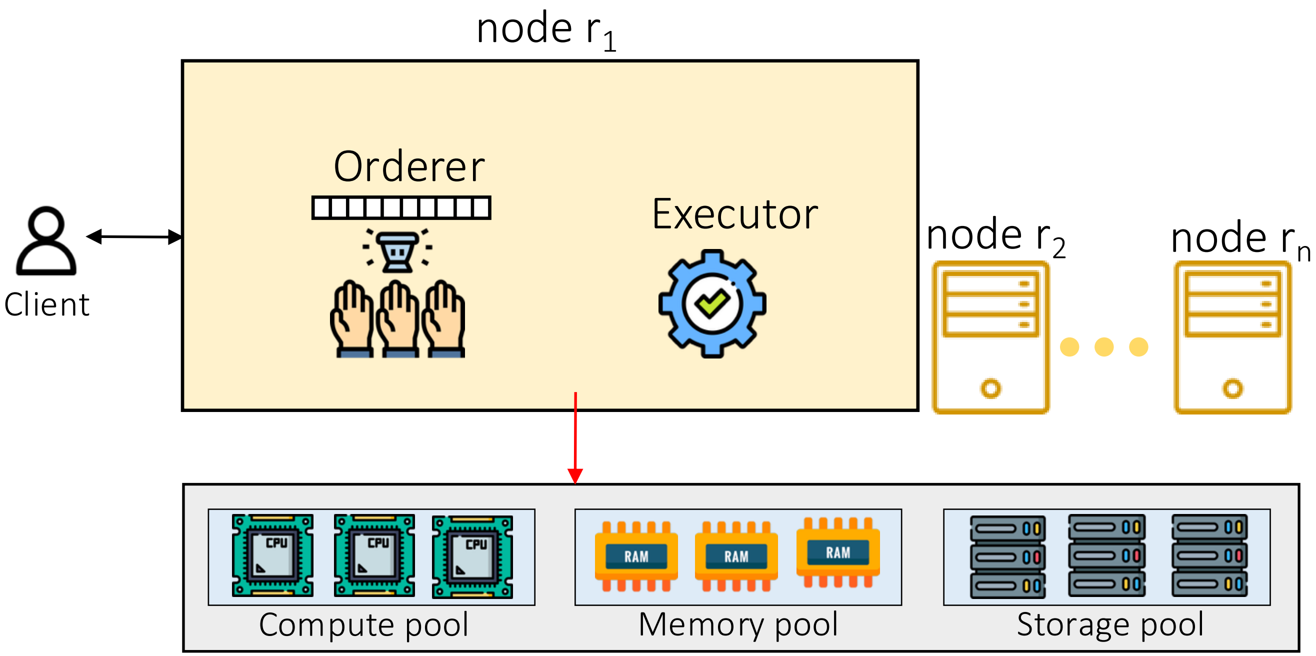


		Condition Parameters					Throughput (tps)			
f	# of clients	# of absentees	request size	proposal slowness	PBFT	Zyzzyva	CheapBFT	Prime	SBFT	HotStuff-2
1	50	0	4KB	0ms	9133	**13664**	11822	4601	11067	6882
4	100	0	4KB	0ms	4316	**10699**	7966	4239	6414	7124
4	100	0	100KB	0ms	4261	6513	**7353**	4177	6518	6779
4	100	4	4KB	0ms	5386	1929	**10011**	4440	5347	8848
4	100	0	0KB	20ms	2435	2424	2433	4265	2432	**6201**
4	100	0	1KB	20ms	2435	2424	2432	4211	2433	**6099**
4	100	0	0KB	100ms	497	498	497	**4257**	497	3641
1	50	0	0KB	20ms	989	988	989	**4527**	989	2640

Various BFT protocols

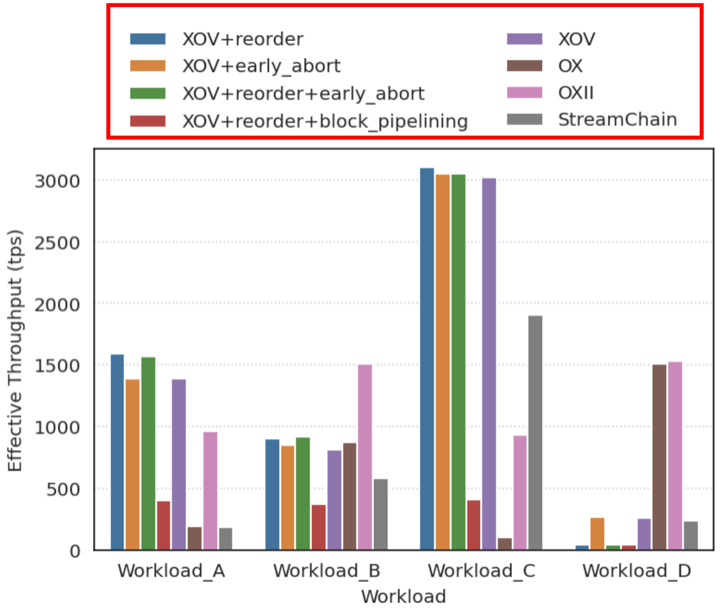
Beyond consensus

- The system performance is affected by other layers as well…
  - Transaction management paradigm
  - Infrastructure (hardware resources)



Challenge 2: transaction management

- **No one-size-fits-all transaction management paradigm**
- Varying design principles
  - The sequence in which ordering/execution/validation are performed, # of transactions in a block, the use of reordering and early aborts
- Transaction workloads fluctuate, nodes join and leave, intermittent faults and attacks

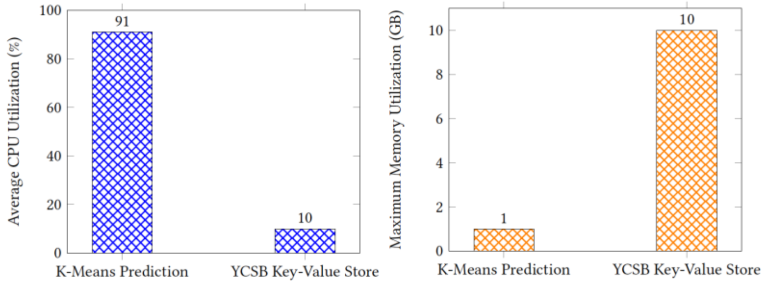


Various transaction management paradigms

Workload	Write Ratio	Contention Level	Load	Compute Intensity
A	low	high	high	high
B	moderate	high	moderate	low
C	moderate	low	high	Very high
D	high	very high	moderate	Very low

Challenge 3: hardware

- **No one-size-fits-all resource provisioning**
- Diverse new applications are emerging every day, each with distinct and heterogeneous resource demands
- A smart contract can interchangably be compute- and memory-intensive at different times and execution stages



Filecoin is making the web more secure and efficient with a decentralized data storage marketplace.
Medicalchain uses blockchain technology to securely manage health data for a collaborative, smart approach to healthcare.
Aggregata is scaling decentralized value of AI Data, powered by DePIN-driven aggregation.

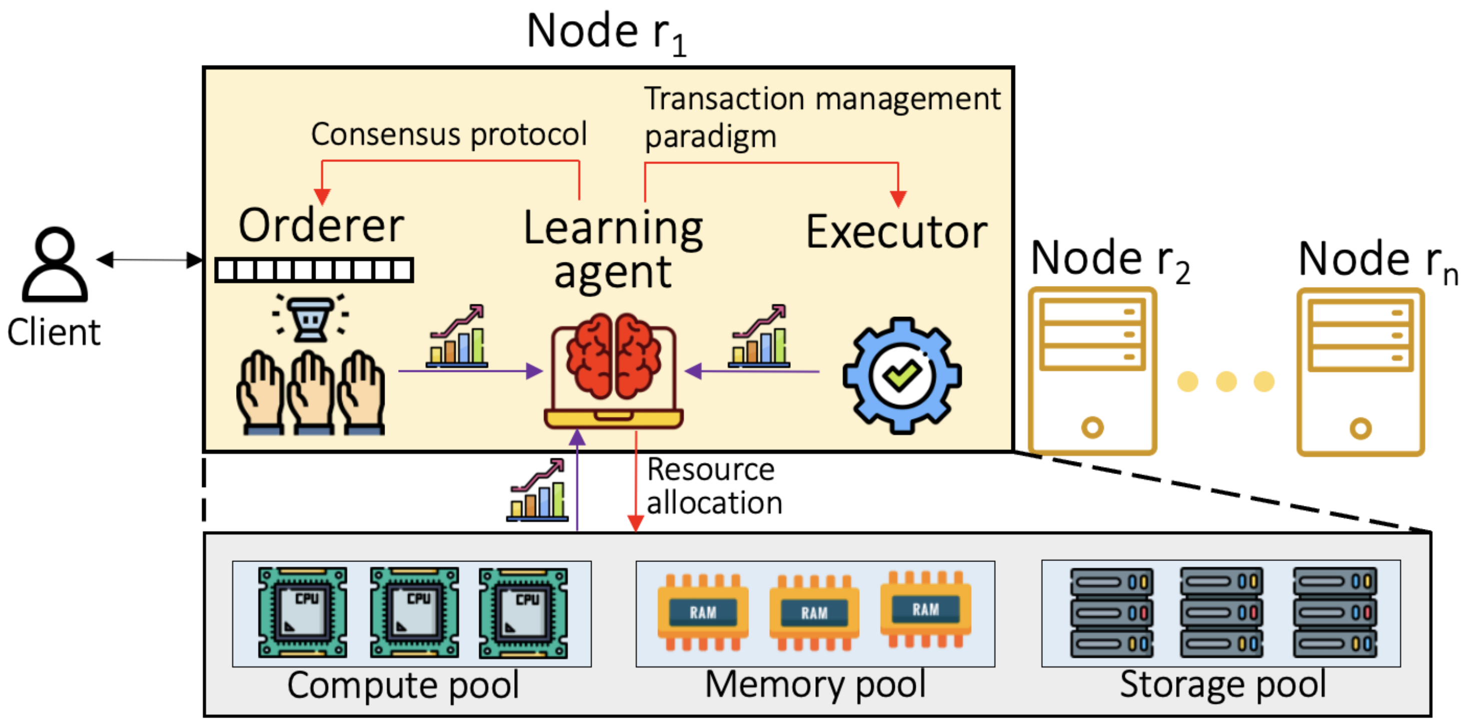
Memory and storage intensive

Nesa is the lightweight Layer-1 executing critical AI inference on queries that require a high degree of privacy, security, and trust using ZKML on-chain.
Holoworld is a decentralized AI character marketplace and social platform where anyone can create powerful, intelligent AI bots with a few clicks.
Story Chain is an innovative multi-level AI-based dApp that fosters collaborative storytelling.

Computation intensive

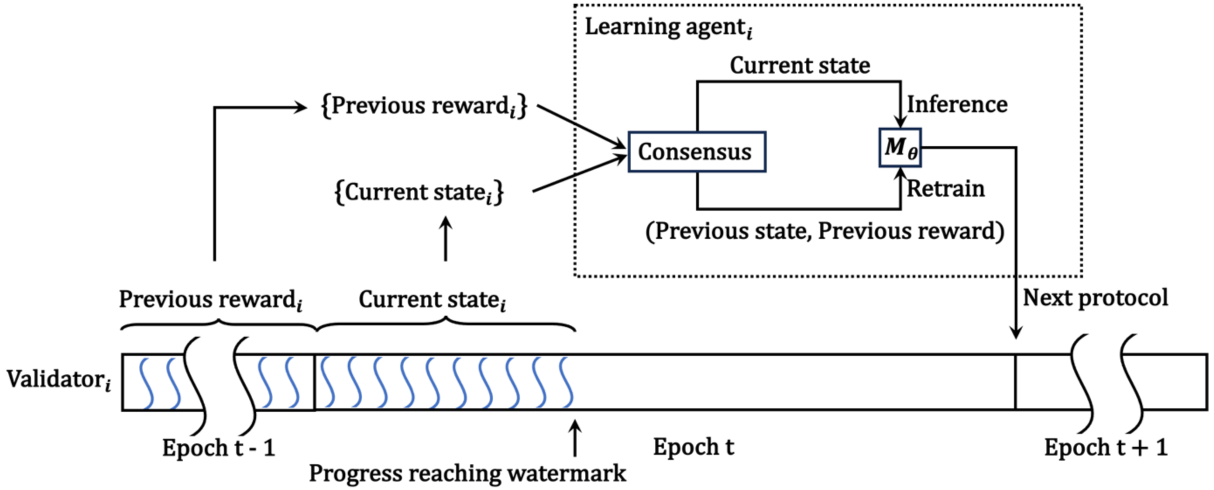
Vision: a fully adaptive system

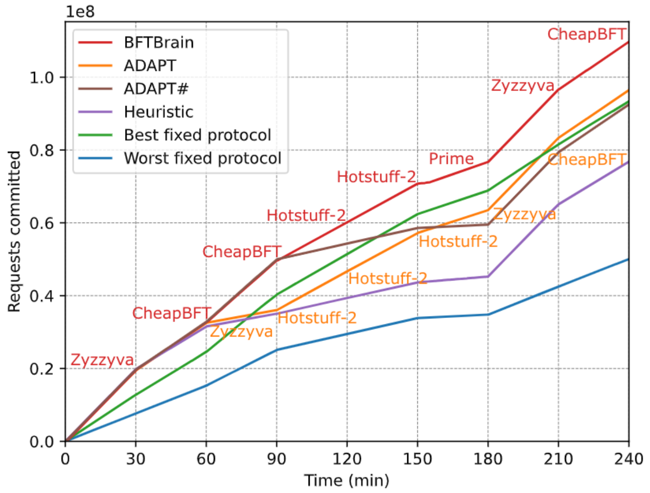
- Leverages machine learning techniques and resource disaggregation to address abovementioned challenges
- Designed with full-stack adaptivity in mind



Adaptive BFT protocol: our first step

- BFTBrain [NSDI’25] uses reinforcement learning techniques to learn the next BFT protocol to switch to *on-the-fly*
- Key innovations
  - Employs novel fine-grained features that offer deeper performance insights, e.g., # of received messages per slot, interval between consecutive leader proposals
  - Decentralized coordinates real-time feature collection and RL engine, resillient to data pollution





Wu, C., Qin, H., Amiri, M. J., Loo, B. T. , Malkhi, D., Marcus, R., BFTBrain: Adaptive BFT Consensus with Reinforcement Learning. NSDI’25

Adaptive BFT protocol: future

- Adversarial machine learning
  - Decision attacks: target the inference phase, an adversary reports false value to disturb the global feature
  - Poisoning attacks: target the training phase, an adversary reports carefully selected feature values and labels to cause the next trained model to be inaccurate
  - How would they affect the system and how to defend against it?

- Protocol specific parameters tuning
  - Continuously tune protocol behavior including internal parameterization, e.g., timer values, batch size

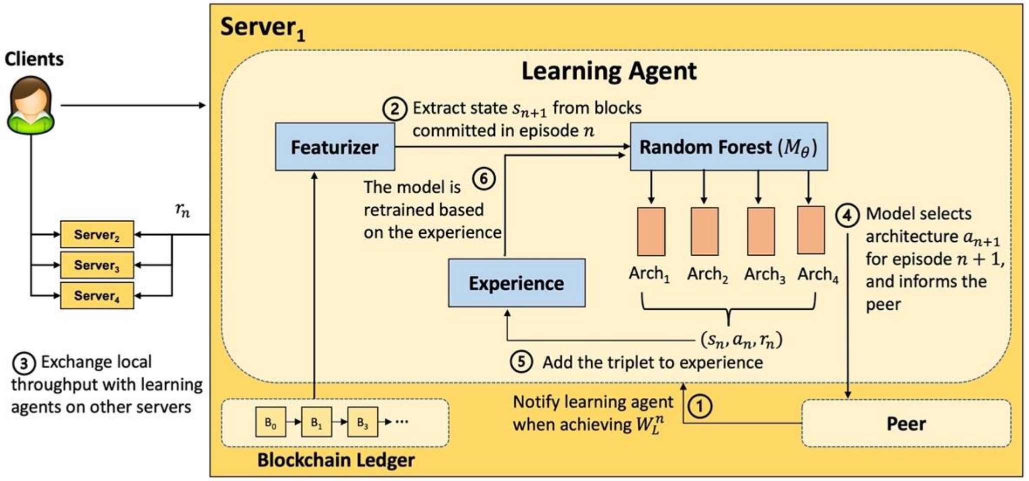
- Reducing overhead
  - Although exploration is inherent, its overhead can be made lower by launching experiments in some "shadow mode" such that mainline performance is not affected

- Discovery of novel protocols
  - Discover new BFT protocols that fit new environments or meet new application requirements through the learning framework, by changing protocol design attributes outlined by Bedrock [NSDI'24]
  - How to systematically ensure and prove the correctness of the newly discovered protocols?

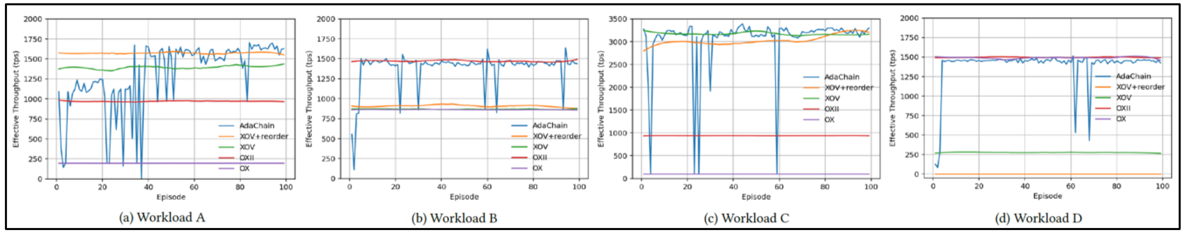
Amiri, M. J., Wu, C., Agrawal, D., El Abbadi, A., Loo, B. T., & Sadoghi, M. The Bedrock of Byzantine Fault Tolerance: A Unified Platform for BFT Protocol Analysis, Implementation and Experimentation, NSDI'24 **[Outstanding Paper Award]**

Adaptive transaction management: our first step

- AdaChain [VLDB'23] uses reinforcement learning to learn the mapping of (workload characteristics -> optimal transaction management paradigm) *on-the-fly*
- Key innovations
  - Models the selection of a paradigm as a contextual multi-armed bandit problem
  - Introduces protocols to switch from one paradigm to another in a live system while respecting correctness and security concerns



Clients
Server$_1$
Learning Agent
② Extract state s_{n+1} from blocks committed in episode n
Featurizer
Random Forest (M_θ)
The model is ⑥ retrained based on the experience
Experience
Arch$_1$
Arch$_2$
Arch$_3$
Arch$_4$
④ Model selects architecture a_{n+1} for episode $n+1$, and informs the peer
(s_n, a_n, r_n)
⑤ Add the triplet to experience
r_n
Server$_2$
Server$_3$
Server$_4$
③ Exchange local throughput with learning agents on other servers
B$_0$
B$_1$
B$_3$
…
Blockchain Ledger
Notify learning agent when achieving W_L^n ①
Peer



(a) Workload A

(b) Workload B

(c) Workload C

(d) Workload D

Wu, C., Mehta, B., Amiri, M. J., Marcus, R., & Loo, B. T. AdaChain: A Learned Adaptive Blockchain, VLDB'23

Adaptive transaction management: future

- Learning strategies
  - Different problem formulation: CMAB (assumes epoch independency) vs. full RL (current action affects the future state)
  - Value-based model vs. policy-based model
  - How well do they perform?

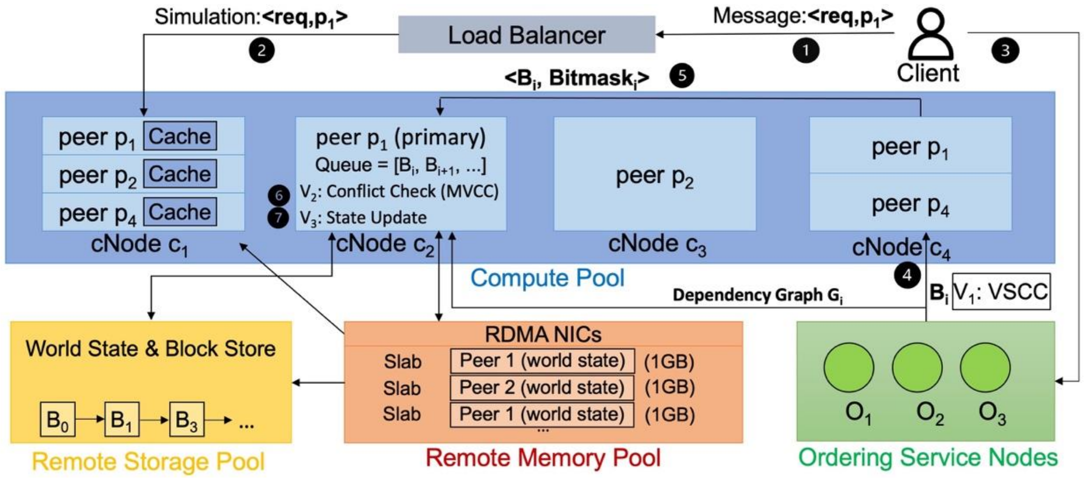
- Featurization
  - Automatic state extraction from ledger (log): deserialize to conflict graph, where each edge is annotated with the submission and commit timestamp, then use GCN to extract the states automatically

- Uncovering new transaction processing paradigms
  - Can learning framework mix and match design attributes? E.g., OXII + reordering + early aborts
  - Consider three transactions: T1(A), T2(A, B), T3(B)

- Finer-grained adaptation
  - Can we directly learn the best final order of transactions, instead of choosing between enabling/disabling the reordering algorithms used by Fabric++?
  - Can we adapt on a per-transaction basis, instead of on a per-epoch basis (a constant number of blocks)?

Adaptive infrastructure: our first step

- FlexChain [VLDB’23]: a disaggregated infrastructure
  - Demonstrating efficient resource utilization and elastic scaling, while incurring at most 12.8% overhead in using remote memory
- Adopts Execute-Order-Validate (XOV) architecture
  - The execution phase is fully in parallel
  - The first part of the validation phase (endorsement policy evaluation) is inherently parallelizable
  - Most of the states resides in key-value stores



Wu, C., Amiri, M. J., Asch, J., Nagda, H., Zhang, Q., & Loo, B. T. FlexChain: an elastic disaggregated blockchain, VLDB’23

Cross-layer adaptivity: future

- Identifying performance bottleneck in an end-to-end system
  - Transaction processing? BFT consensus? Under-provisioned resource?
  - Avoid unnecessary configuration switching or resource over-provisioning

- Disaggregation or not?
  - How do other transaction processing paradigms (other than XOV) perform on DDCs?
  - Given the current workload and remote memory overhead, is it worthwhile to disaggregate?
  - View the blockchain ledger as multi-channel time series data, and forecast the workload changes that should lead to a transition in infrastructure

Questions?