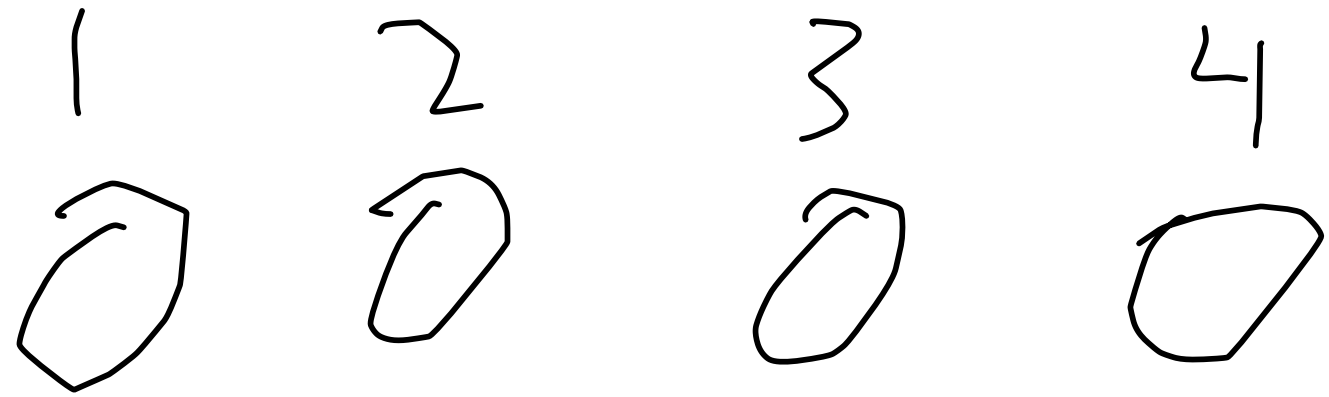


primary = v % (3f+1) + 1

Round 1: Ensure f+1 honest replicas agree: if req. r executed in v, will have seq. no. n

Round 2: f+1 honest replicas agree: r executed in v w. seq# n

C r_i R P

C → P: $m = \langle REQUEST, o, t, c \rangle_{K_c}$

P → R: $\langle PRE\text{-}PREPARE, v, n, d \rangle_{K_p}, m$

r_i → R: $\langle PREPARE, v, n, d, i \rangle_{K_{r_i}}$

wait for PRE-PREPARE + 2f matching PREPARE prepared(m, v, n, i)

⟹ cannot have prepared(m', v, n, i)

where $m' \neq m$

C r_i R P

C → P : $m = \langle REQUEST, o, t, c \rangle_{K_c}$

P → R : $\langle PRE\text{-}PREPARE, v, n, d \rangle_{K_p}, m$

r_i → R : $\langle PREPARE, v, n, d, i \rangle_{K_{r_i}}$

wait for PRE-PREPARE + 2f matching PREPARE
prepared(m, v, n, i)

r_i → R : $\langle COMMIT, v, n, d, i \rangle$

wait for 2f+1 matching COMMIT
committed-local(m, v, n, i)

r_i → C : $\langle REPLY, v, t, c, i, r \rangle$

client waits for f+1 matching REPLY

committed(m, v, n) non-faulty

prepared(m, v, n, i) for $f+1 \wedge r_i$

committed-local at one node

$\Rightarrow$ committed

Checkpoints

⟨CHECKPOINT, n, d, i⟩

stable checkpoint = 2f+1 matching CHECKPOINTS

n = h seq. no. valid up to H = h + k

$r_i \rightarrow R$: ⟨VIEW-CHANGE, v+1, n, C, P, i⟩

C → 2f+1 CHECKPOINTS

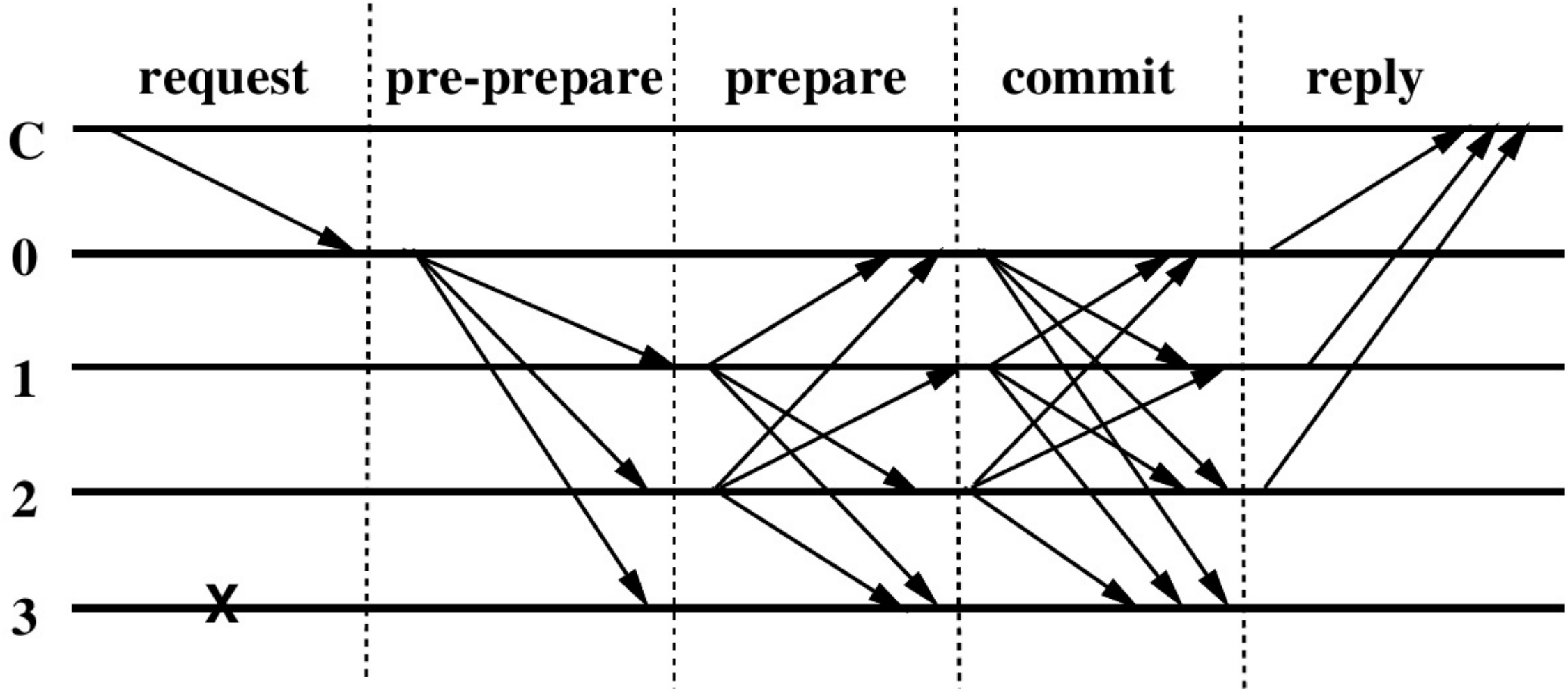
P → {P_m} P_m PRE-PREPARE + 2f PREPARES

Primary p of v+1 waits for 2f VIEW-CHANGE from others

$p \rightarrow R$: ⟨NEW-VIEW, v+1, V, O⟩

V = 2f VIEW-CHANGES + P's VIEW-CHANGE

O = Set of PRE-PREPARES


request
pre-prepare
prepare
commit
reply
C
0
1
2
3
X

arg./res. (KB)	replicated		without replication
	read-write	read-only	
0/0	3.35 (309%)	1.62 (98%)	0.82
4/0	14.19 (207%)	6.98 (51%)	4.62
0/4	8.01 (72%)	5.94 (27%)	4.66

Table 1: Micro-benchmark results (in milliseconds); the percentage overhead is relative to the unreplicated case.

phase	BFS		BFS-nr
	strict	r/o lookup	
1	0.55 (57%)	0.47 (34%)	0.35
2	9.24 (82%)	7.91 (56%)	5.08
3	7.24 (18%)	6.45 (6%)	6.11
4	8.77 (18%)	7.87 (6%)	7.41
5	38.68 (20%)	38.38 (19%)	32.12
total	64.48 (26%)	61.07 (20%)	51.07

Table 2: Andrew benchmark: BFS vs BFS-nr. The times are in seconds.

phase	BFS		NFS-std
	strict	r/o lookup	
1	0.55 (-69%)	0.47 (-73%)	1.75
2	9.24 (-2%)	7.91 (-16%)	9.46
3	7.24 (35%)	6.45 (20%)	5.36
4	8.77 (32%)	7.87 (19%)	6.60
5	38.68 (-2%)	38.38 (-2%)	39.35
total	64.48 (3%)	61.07 (-2%)	62.52

Table 3: Andrew benchmark: BFS vs NFS-std. The times are in seconds.