
motr
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a scalable storage platform

Motr goals

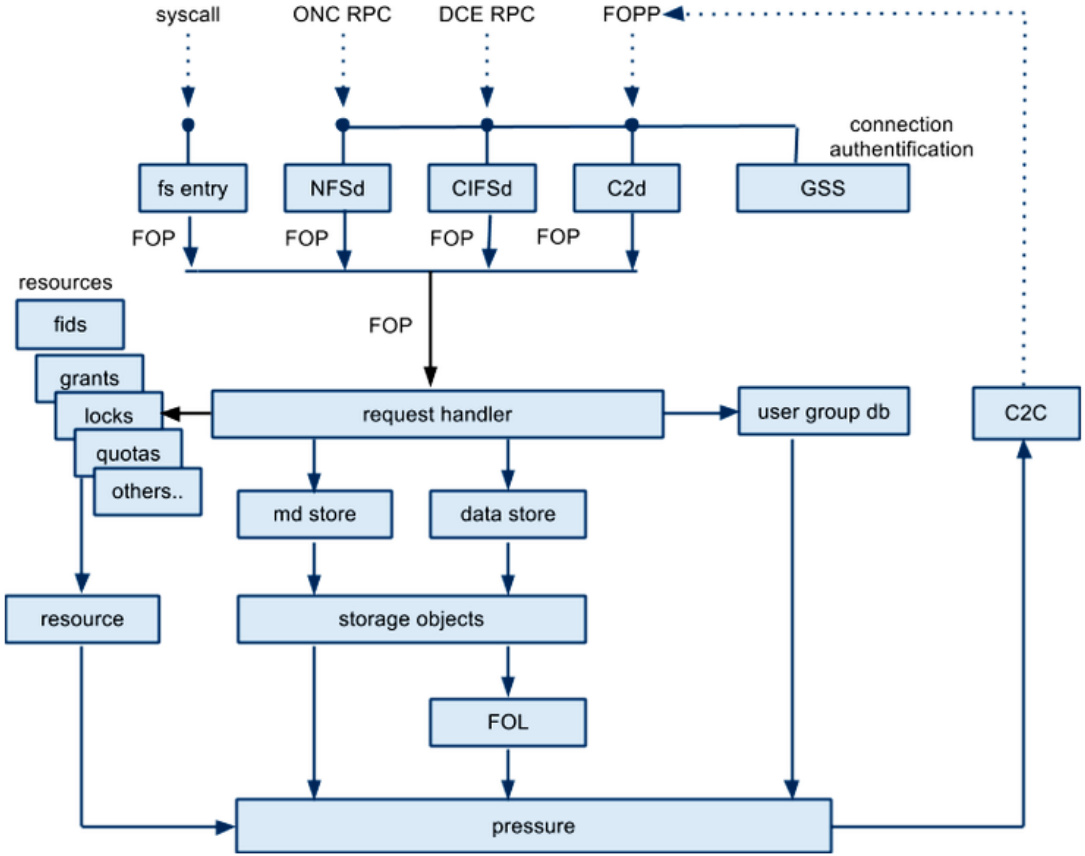
- extensible storage platform
  - observability
  - extensible scalable 3rd party plugins
- horizontally scalable (number of devices and nodes)
- vertically scalable (number of cores)
- flexible deployment

Warning: not everything in this presentation is fully implemented.

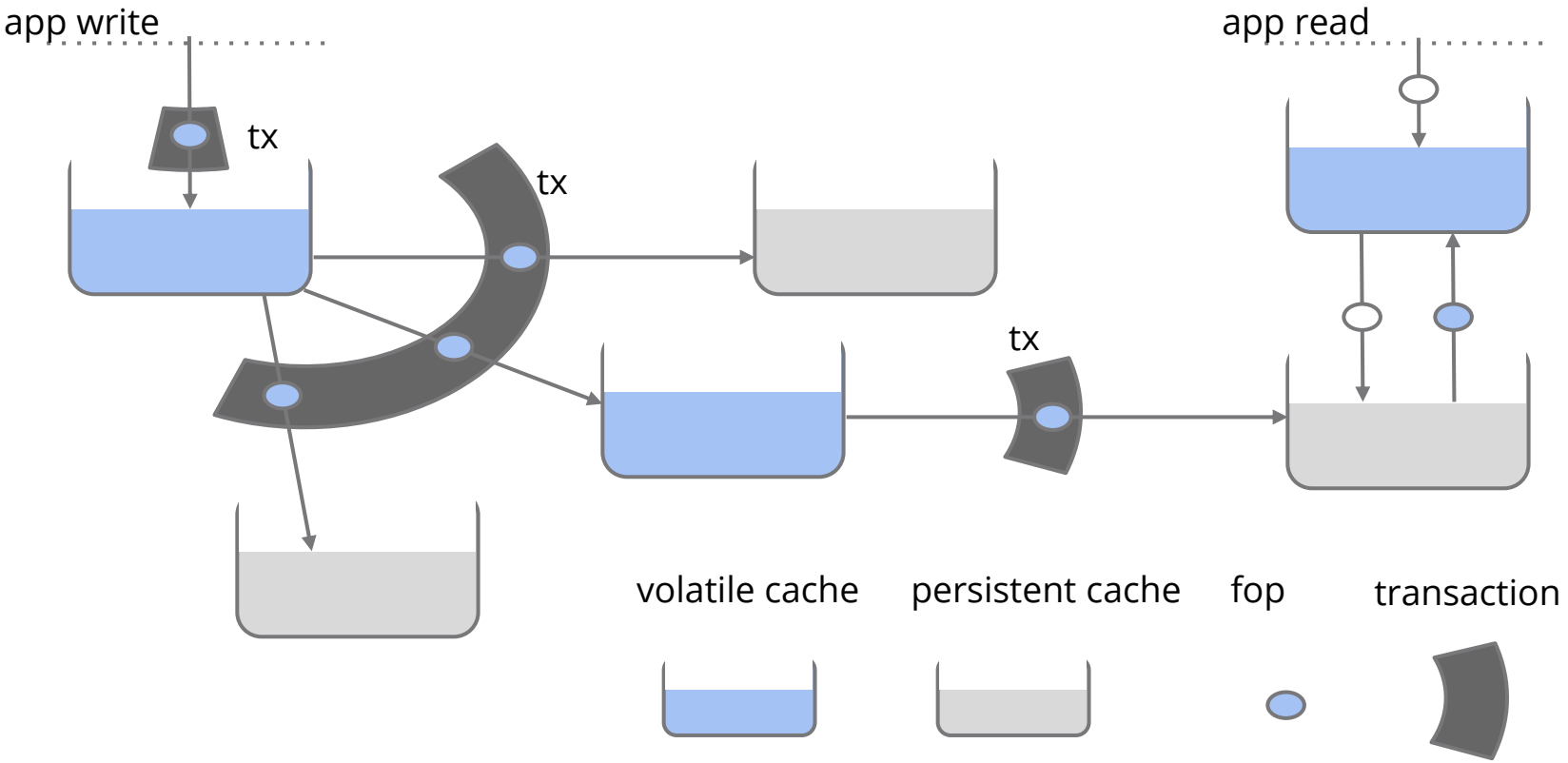
features

- 0-copy, 2-phase IO
- extensible meta-data: distributed key-value store
- layouts (data, meta-data, fault-tolerance)
  - network striping (parity de-clustering)
  - composite: NBA, snapshot, multi-tier
- distributed transactions (consistency)
- resource manager (coherency)
- containers, function shipping
- threadless server design
- fdmi, addb
- user space, portable

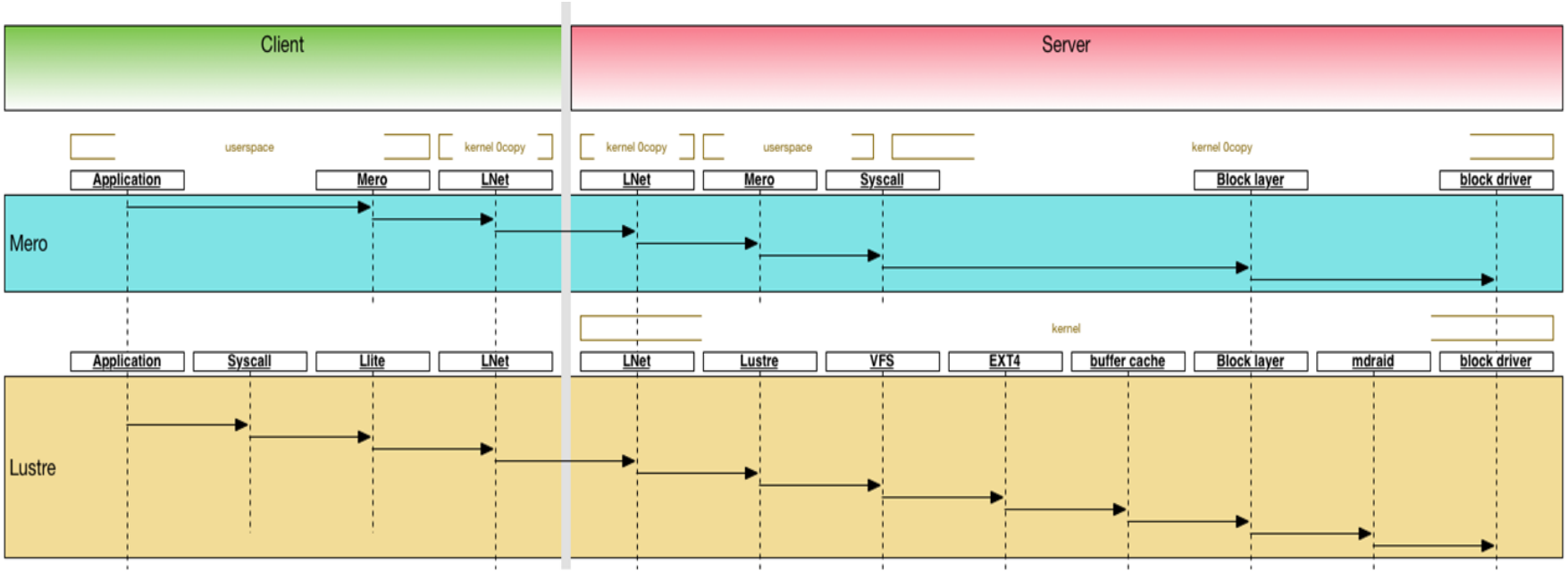
structure: instance (single node, process or kernel)



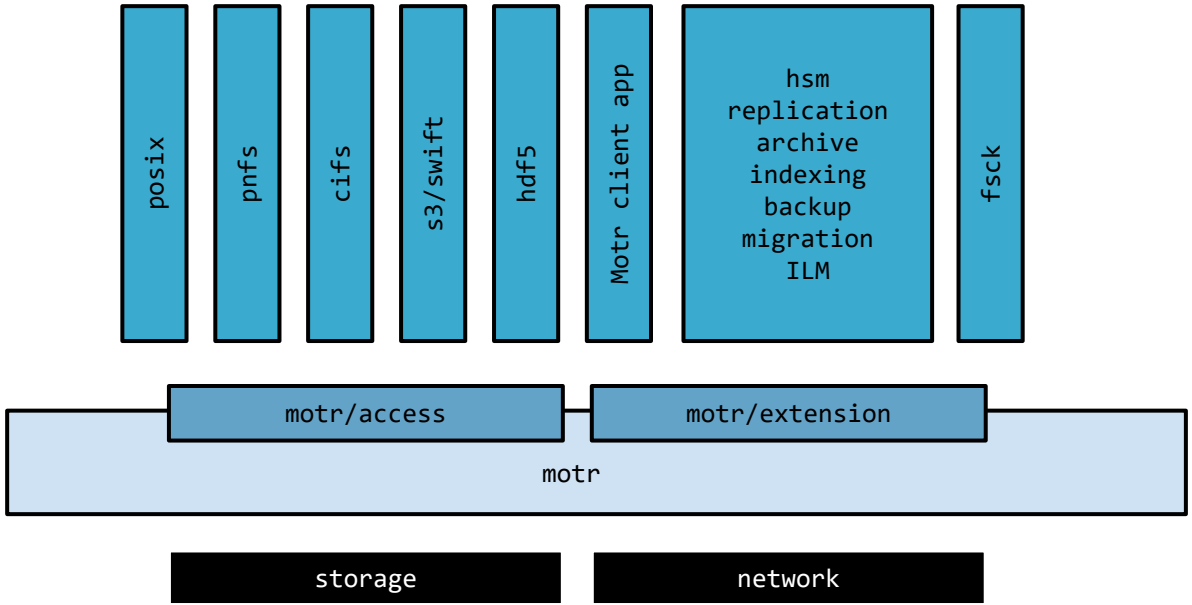
structure: system view



structure: (non-)layering



structure: components



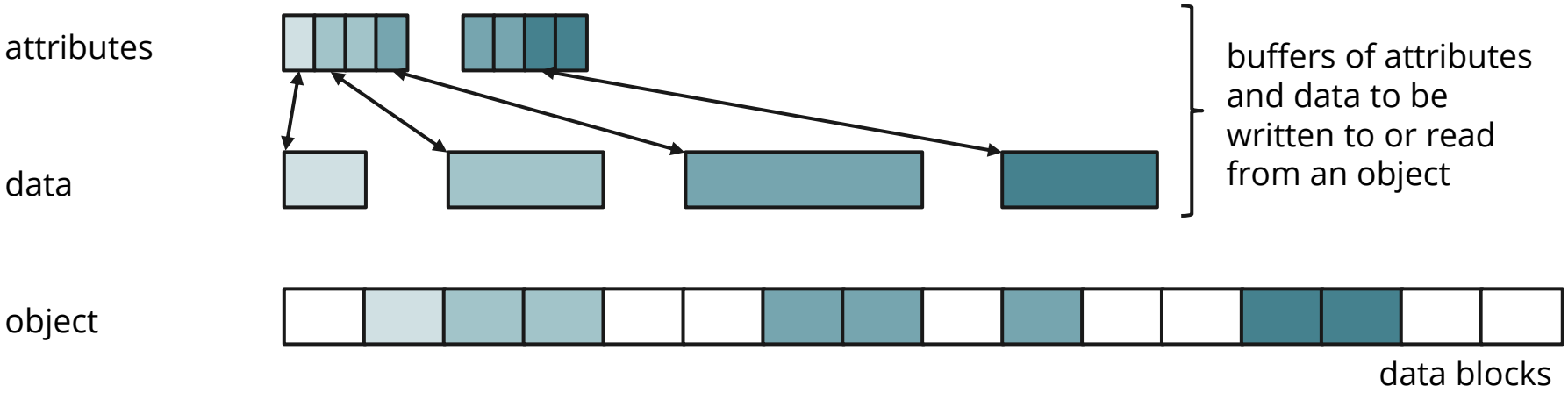
components

- **Motr client**
- transactions (dtm)
- resource manager
- fdmi
- addb
- network raid, layouts
- containers
- function shipping
- lingua franca
- integrity checking
- meta-data back-end
- network, rpc, fop, HA
- fom, reqh
- device io (stob)
- network raid repair
- security

Motr client: overview

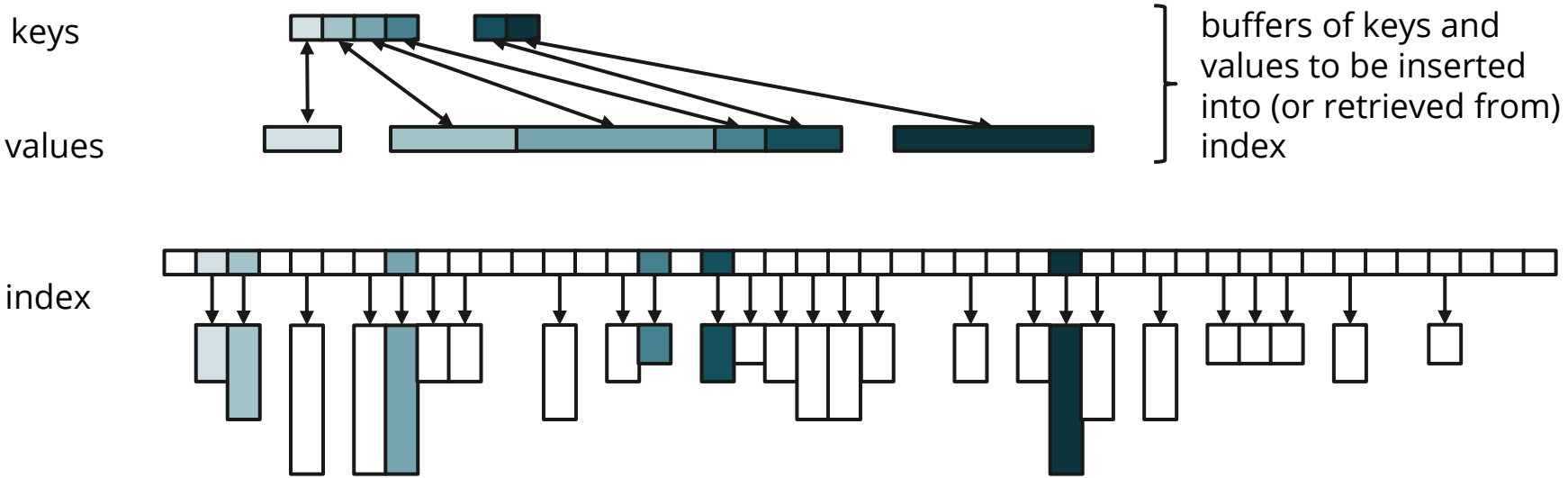
- object: network striped by default
- index: distributed key-value store
- operation: asynchronous, state machine, tracks progress
- transaction: atomic group of operations
- resource: ownership, coherent distributed caching
- layout: placement of data on storage
- 128-bit persistent identifiers, assigned by user
- all entry-points are asynchronous

Motr client: object



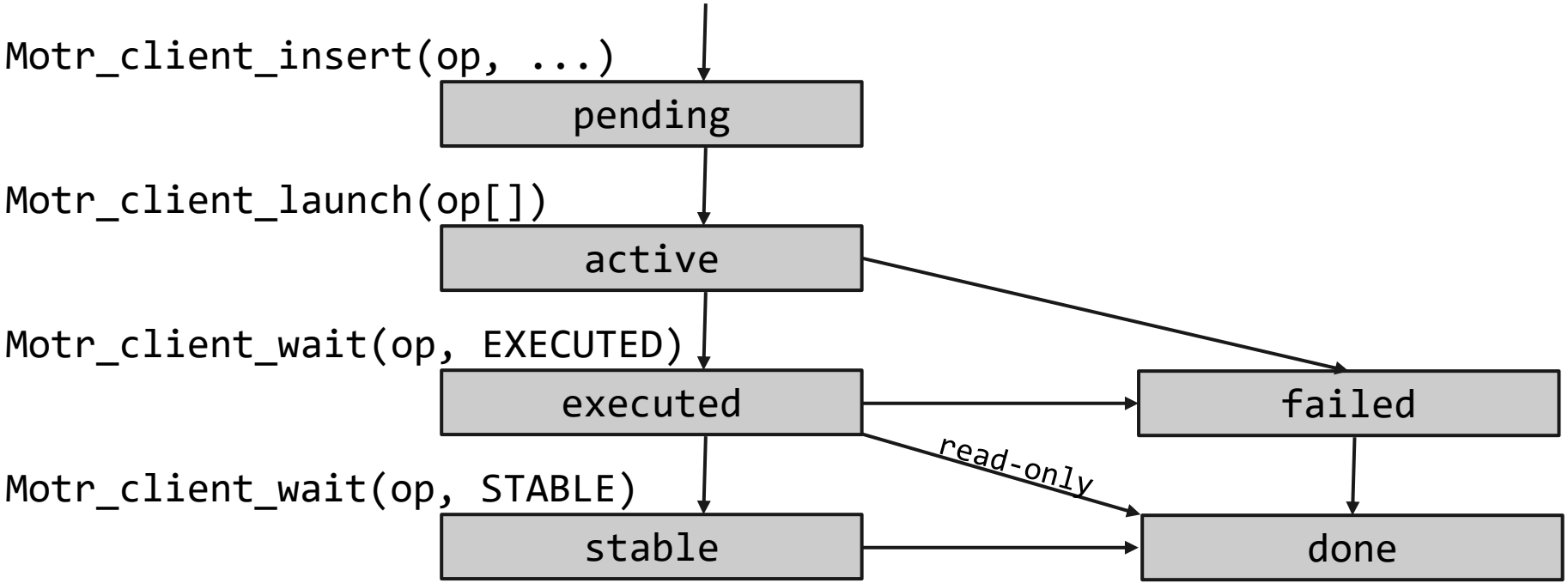

```
Motr_client_read(op, obj, data_buf_vec, attr_buf_vec, extent_vec)
Motr_client_write(op, obj, tx, data_buf_vec, attr_buf_vec, extent_vec)
Motr_client_alloc(op, obj, tx, extent_vec)
Motr_client_free(op, obj, tx, extent_vec)
```

Motr client: index




```
Motr_client_lookup(op, index, key_buf_vec, val_buf_vec)
Motr_client_insert(op, index, tx, key_buf_vec, val_buf_vec)
Motr_client_next(op, index, key_buf_vec, val_buf_vec)
```

Motr client: operation



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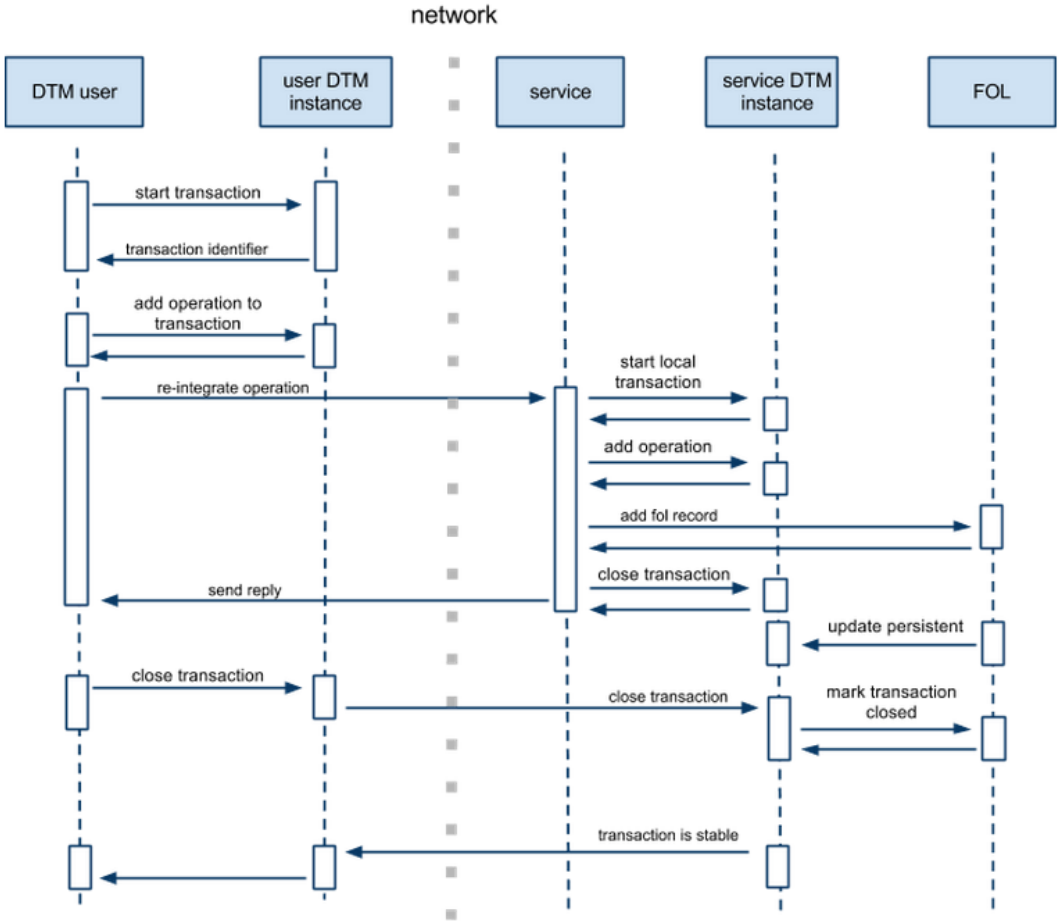
dtm: transactions

- a transaction is a group of operations
- **a**tomicity w.r.t. certain failures (network partitions, node restarts)
- **c**onsistency is defined by user
- guarantees neither **i**solation nor serialisability
- doesn't guarantee synchronous **d**urability: too expensive for small transactions. Asynchronous stabilisation: the user is notified when the transaction becomes stable
- stabilisation ordering, liveness

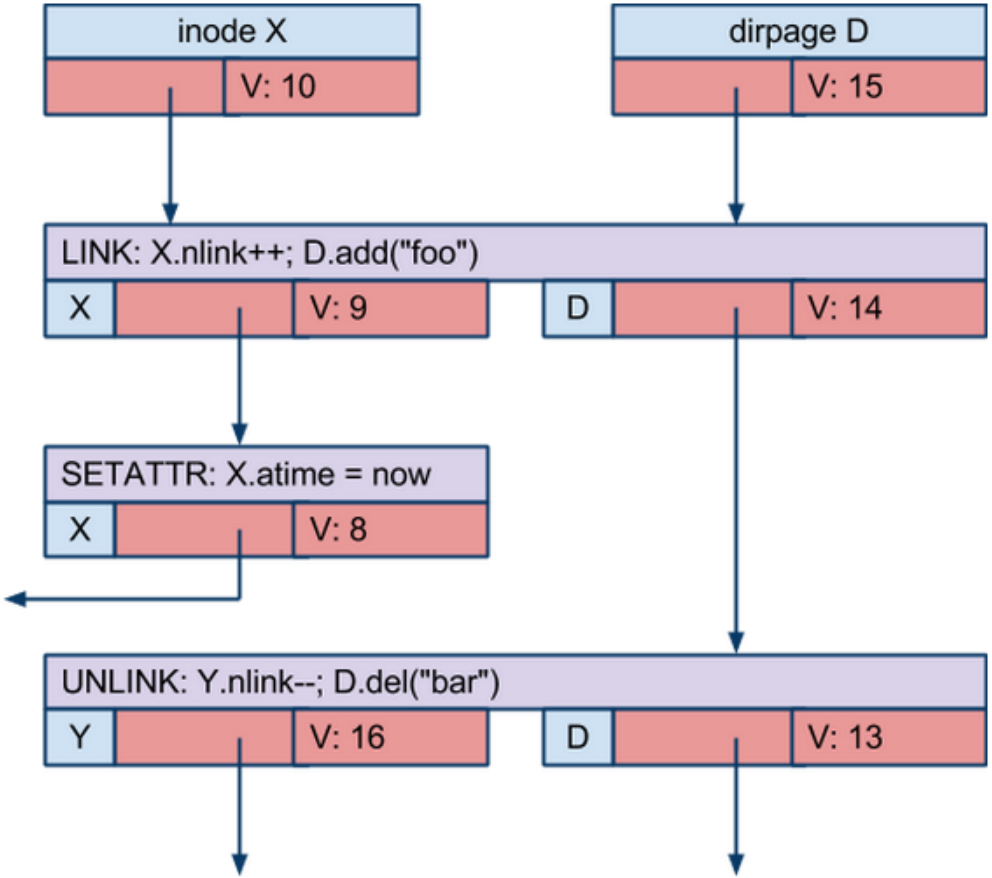
dtm: sequence



dtm: features

- masks certain transient failures
  - network partition, re-ordering, duplication
  - node restart
- write-ahead logging on each server
- undo for data
- redo for meta-data
- stabilisation: global logical clock (epochs)

dtm: versions

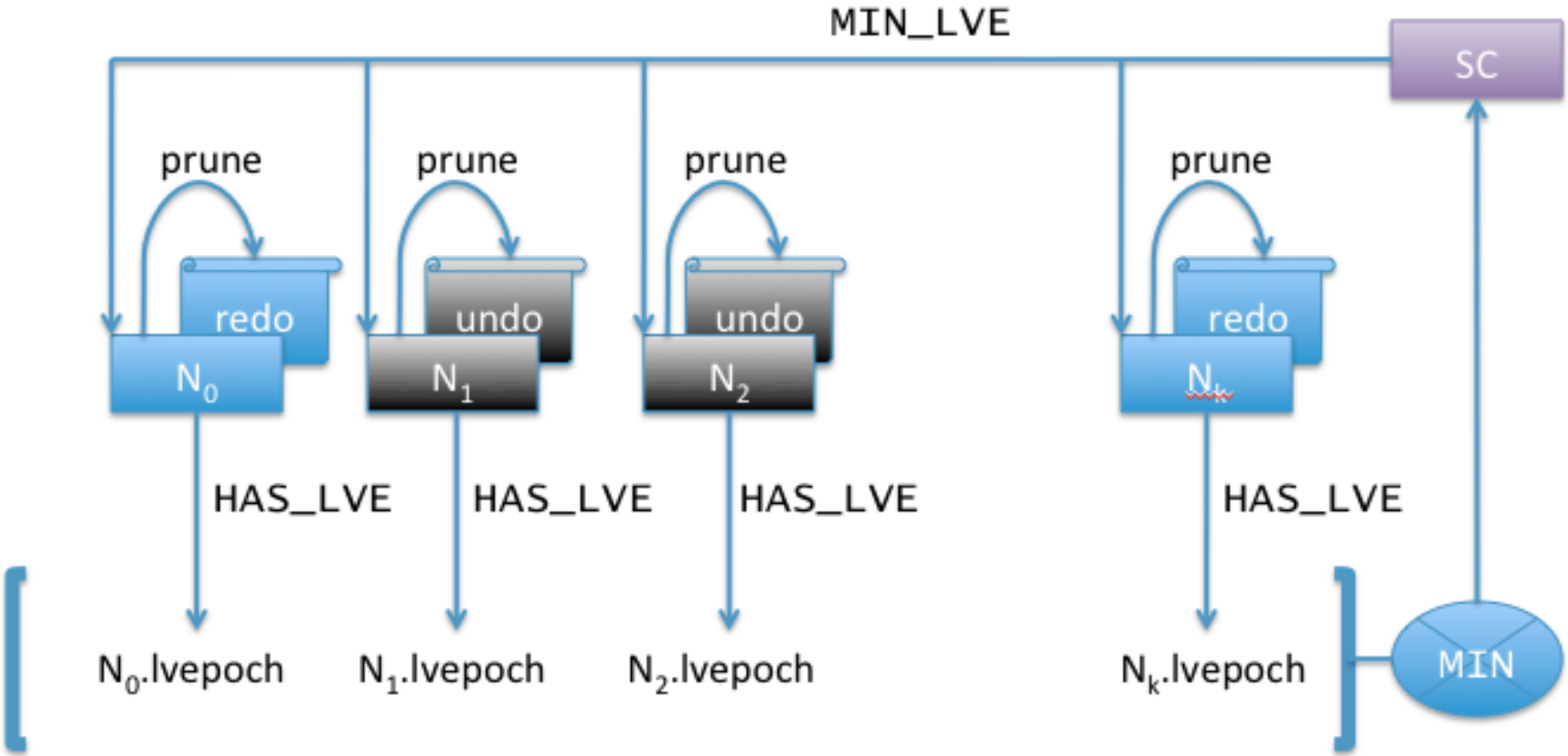


dtm: epochs

- distributed clock to detect operation dependency and ordering (epoch, Fidge-Mattern, Lamport)
- messages are tagged with the logical timestamps:

  `Event1` depends on `Event0`, then `Event0.epoch <= Event1.epoch`
- any node can advance its clock independently
- operations are kept in the persistent log in epoch order, until epoch is stable. Then the log is pruned
- global coordination to determine when an epoch is stable

dtm: epochs



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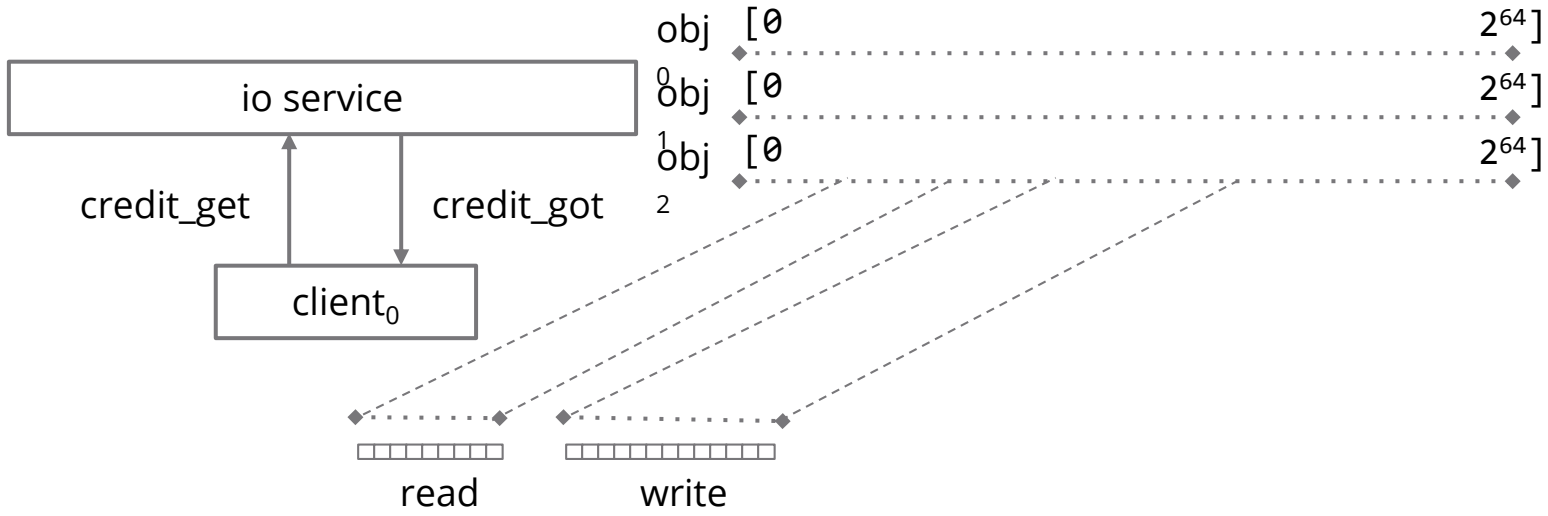
rm: definition

- resource: anything with ownership. An extent in an object, an entire object, a key in an index, *etc*.
- credit: a right to use a resource in a particular way
- credits control:
  - distributed caching
  - concurrency
- credits can be borrowed and sublet
- resource manager is separate from resource
- resource manager resolves conflicts
- user can define new resource types

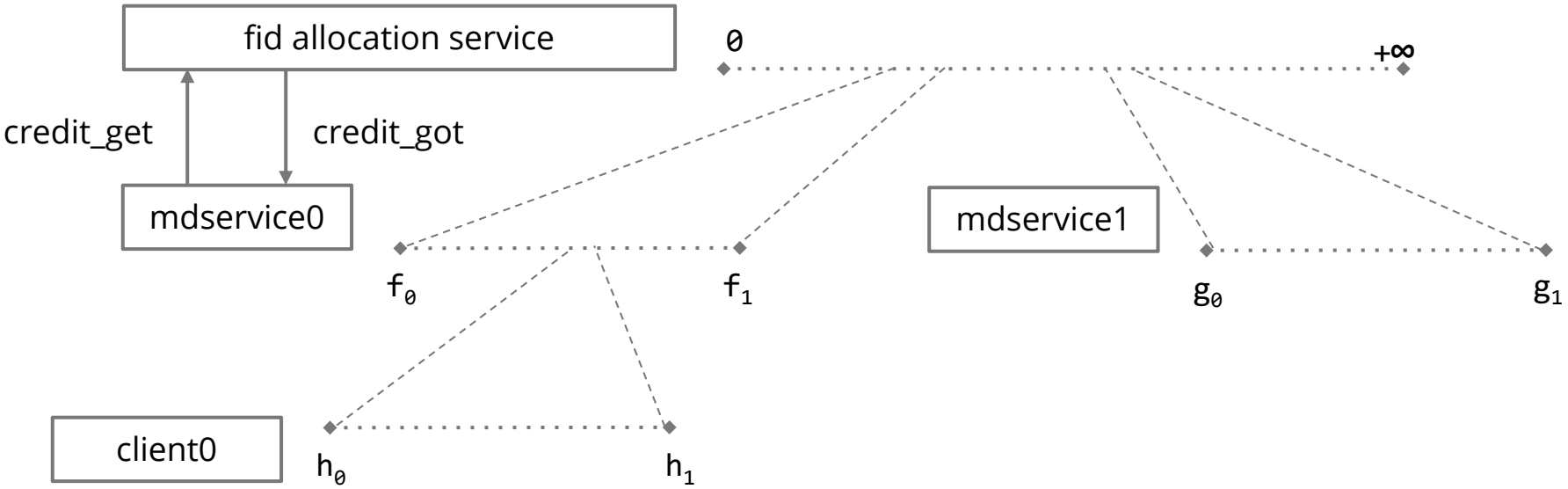
rm: use case

Example: Block extent in a Motr client object



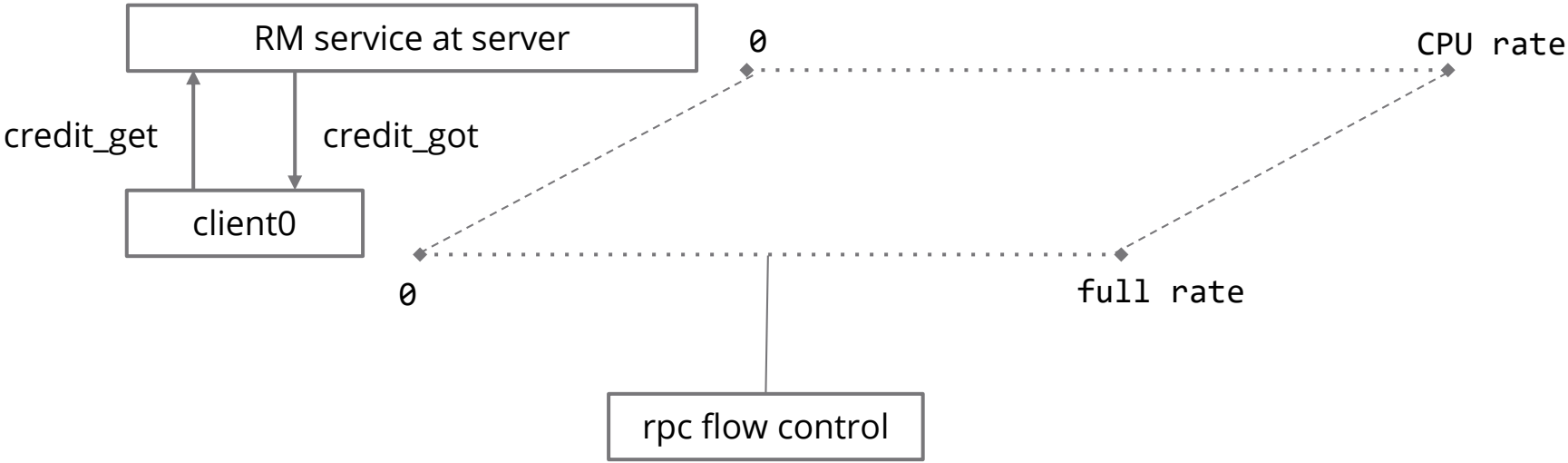
rm: use case

Example: fid extent allocation. Fid: 128 bit.



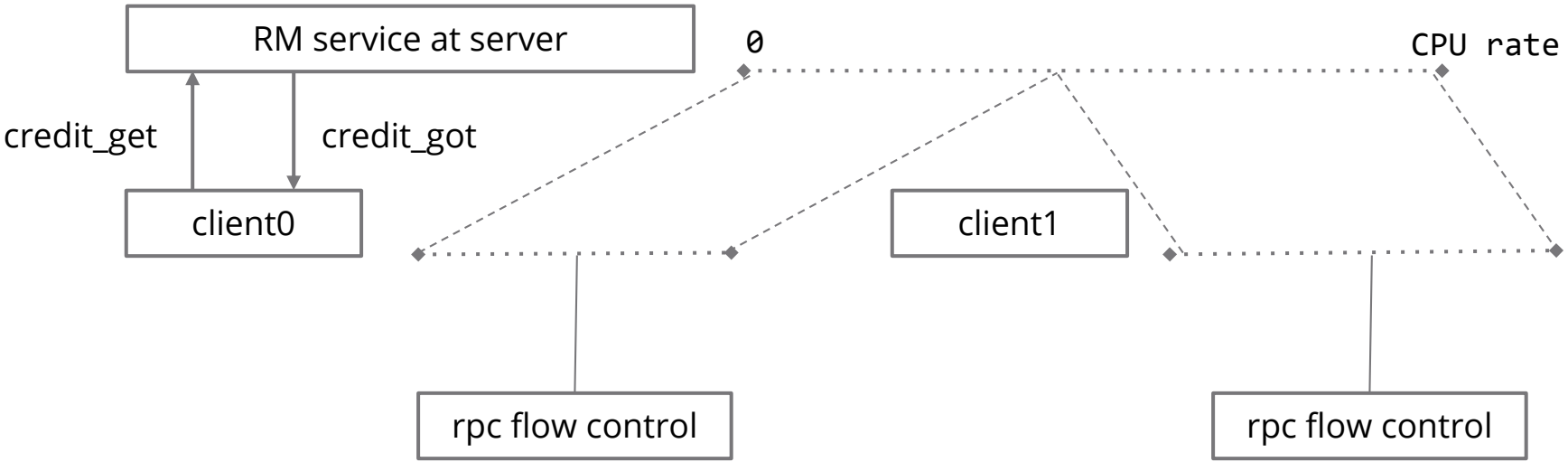
rm: use case

Example: server CPU cycles

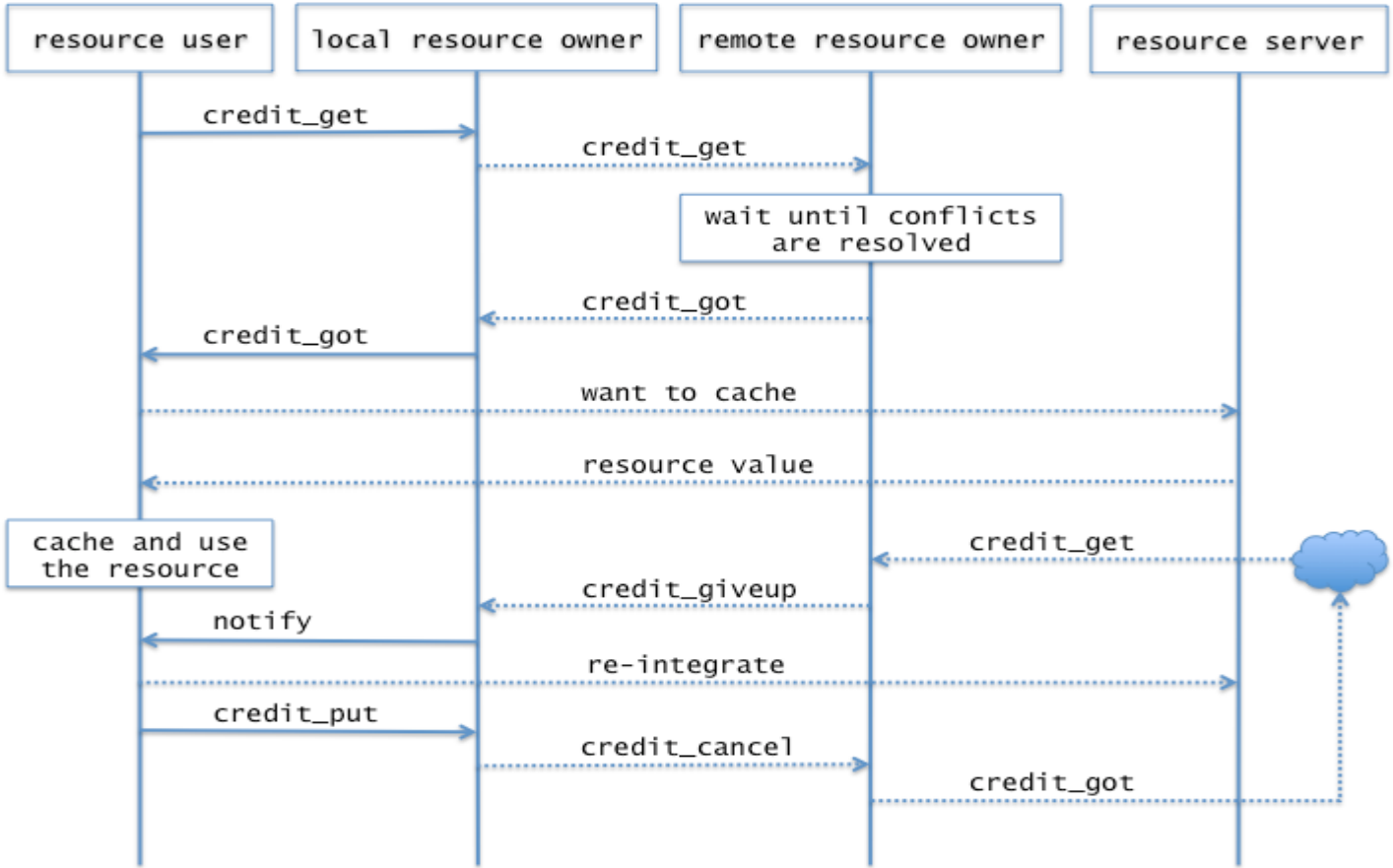


rm: use case

Example: server CPU cycles



rm: sequence



rm: resources

Resource types

- open-files
- file extents
- disk space (grants)
- quotas
- server memory
- server cpu cycles
- file identifiers (fids)
- inode numbers
- network bandwidth
- storage bandwidth
- layout
- cluster configuration
- power

rm: resource manager context

- generic infrastructure:
  - RM service: BORROW, REVOKE, CANCEL
  - client (Motr client) interface
- specific resource types:
  - resource and credit names
  - conflict, credit ordering
- RM users:
  - resource acquisition and release logic
  - cache invalidation
  - assignment of RM services

components

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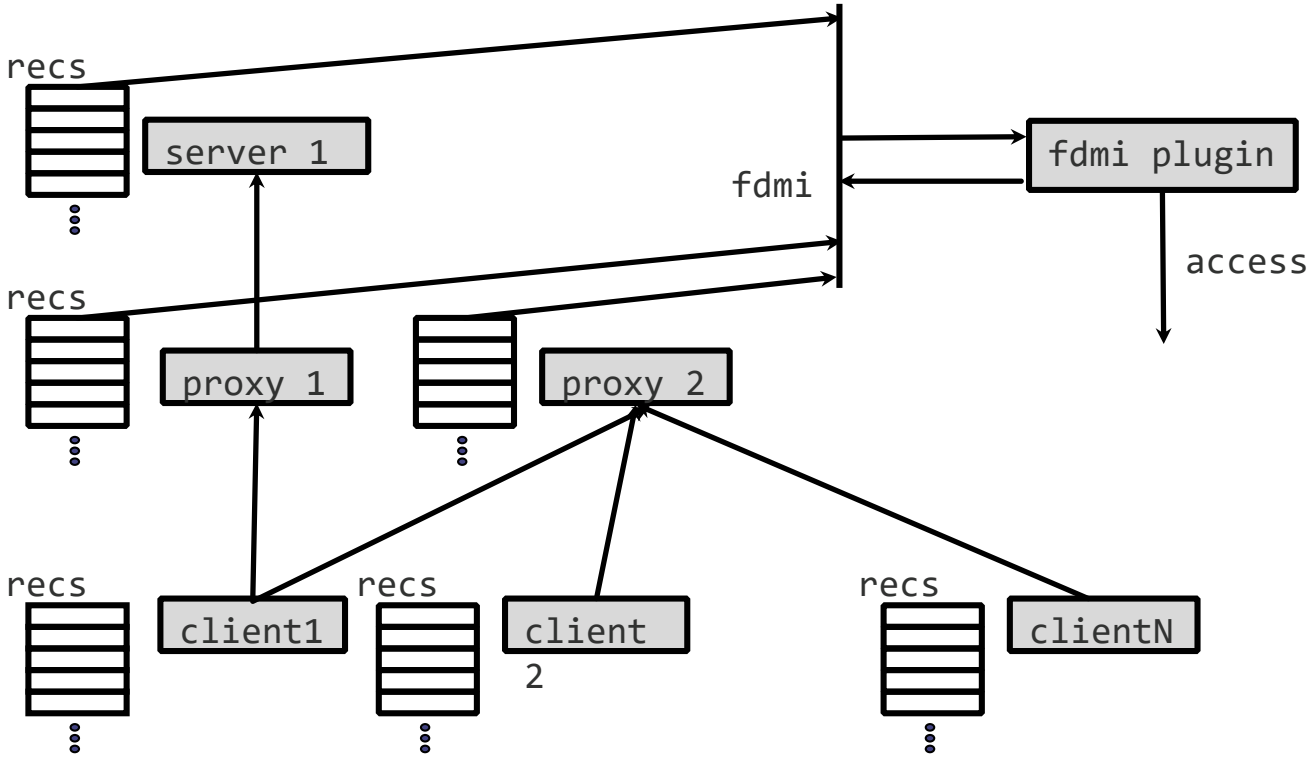
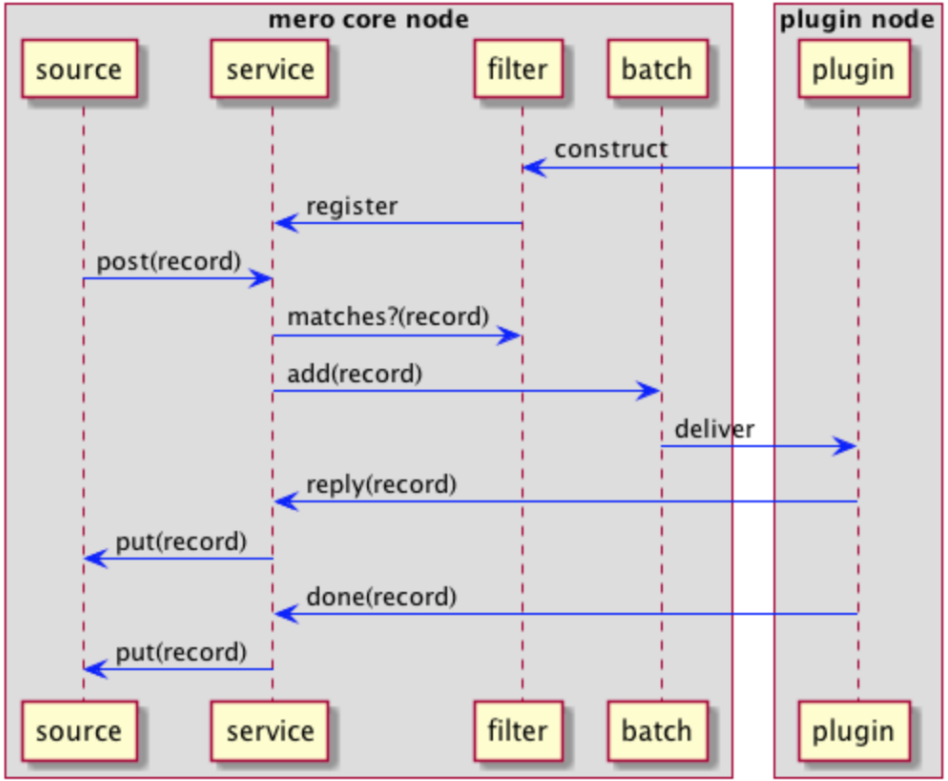
fdmi

- operation log (fol):
  - record each operation on an object
  - log consists of records, log maintained by each node
- file-system definition and manipulation interface (fdmi)
  - scalable publish-subscribe interface
  - subscribe to records matching certain filter
  - map-reduce-style mechanism to deliver matching records to the subscribers
  - transactional delivery (EOS)
  - delivers: fol records, addb records, HA events, others
- horizontal scalability
  - offload plugin processing and data-structures
  - asynchronous processing, batching

fdmi

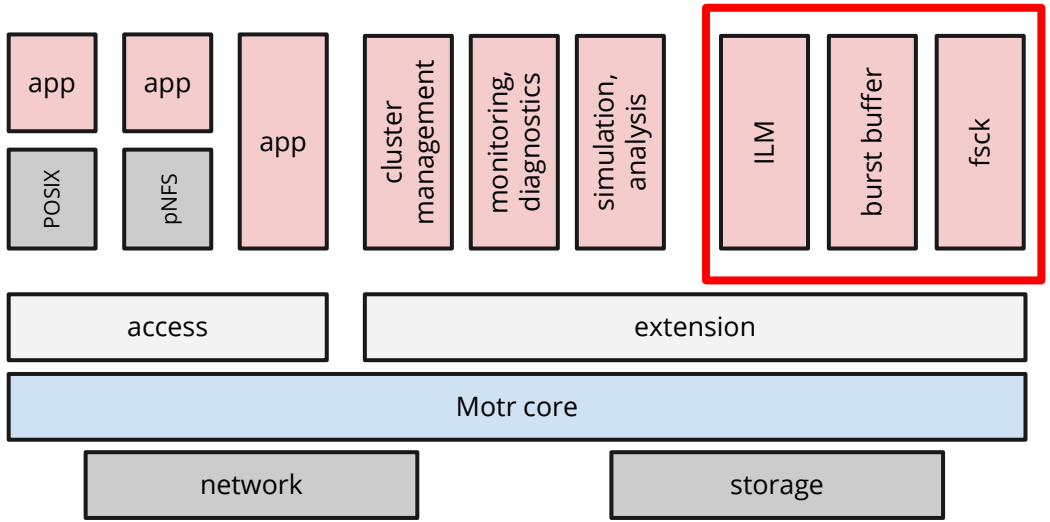


fdmi



fdmi

- ILM
  - replication
  - migration
  - backup, archival,
  - hsm
- indexing
- fsck
- data re-structuring
  - proxy de-staging
  - RAID re-striping
- guided interfaces
  - profiling
  - prefetching, destaging



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addb

- systems grow larger and more complex
- how well the system is utilised?
- is it failure or expected behaviour?
- is it system or application behaviour?
- sources of data:
  - system logs
  - operating system
  - application traces
- very large amount of collected data
- ... or insufficiently detailed, or both
- difficult to analyse and correlate

addb

- instrumentation on client and server
- data about operation execution and system state
- passed through network
- cross-referenced
- always on (post-mortem analysis, first incident fix)
- simulation (change configuration, larger system, load mix)

```
* 2015-04-20-14:36:13.687531192 alloc size: 40, addr: @0x7fd27c53eb20
|  node             <f3b62b87d9e642b2:96a4e0520cc5477b>
|  locality         1
|  thread           7fd28f5fe700
|  fom              @0x7fd1f804f710, 'IO fom' transitions: 13 phase: Zero-copy finish
|  stob-io-launch   2015-04-20-14:36:13.629431319, <200000000000003:10000>, count: 8, bvec-nr: 8, ivec-nr: 1, offset: 0
|  stob-io-launch   2015-04-20-14:36:13.666152841, <100000000adf11e:3>, count: 8, bvec-nr: 8, ivec-nr: 8, offset: 65536
```

addb: anatomy of a record

```
* 2015-04-14-15:33:11.998165453 fom-descr service: <7300000000000001:0>, sender: c28baccf27e0001, req-opcode: Read request,
  rep-opcode: Read reply, local: false
|         node             <11186d8bf0e34117:ab1897c062a22573>
|         locality         3
|         thread           7f79e57fb700
|         ast
|         fom              @0x7f795008ed20, 'IO fom', transitions: 0, phase: 0
```

- measurement and context
- timestamped
- labels: identify context
- payload: up to 16 64-bit values,
- interpreted by consumer

addb: sensors and histograms

```
* 2018-04-05-14:27:40.563070315 fom-active nr: 710 min: 0 max: 24 avg: 5.029577 dev: 11.147012
  1 1: 226 3: 313 5: 98 7: 26 9: 20 11: 8 13: 5 15: 6 17: 4 19: 3 21: 0 23: 0 25: 0
|         node             <5e341757d0cf46eb:92a6d6e991b46387>
|         pid              6627
|         locality         0
```

- some events are too frequent
- collapse them into counters
- count last events per locality
- automatically size buckets

```
   :   1 |
 1 : 226 | **********************
 3 : 313 | ******************************
 5 :  98 | **********
 7 :  26 | ***
 9 :  20 | **
11 :   8 | *
13 :   5 |
15 :   6 |
17 :   4 |
19 :   3 |
21 :   0 |
23 :   0 |
25 :   0 |
```

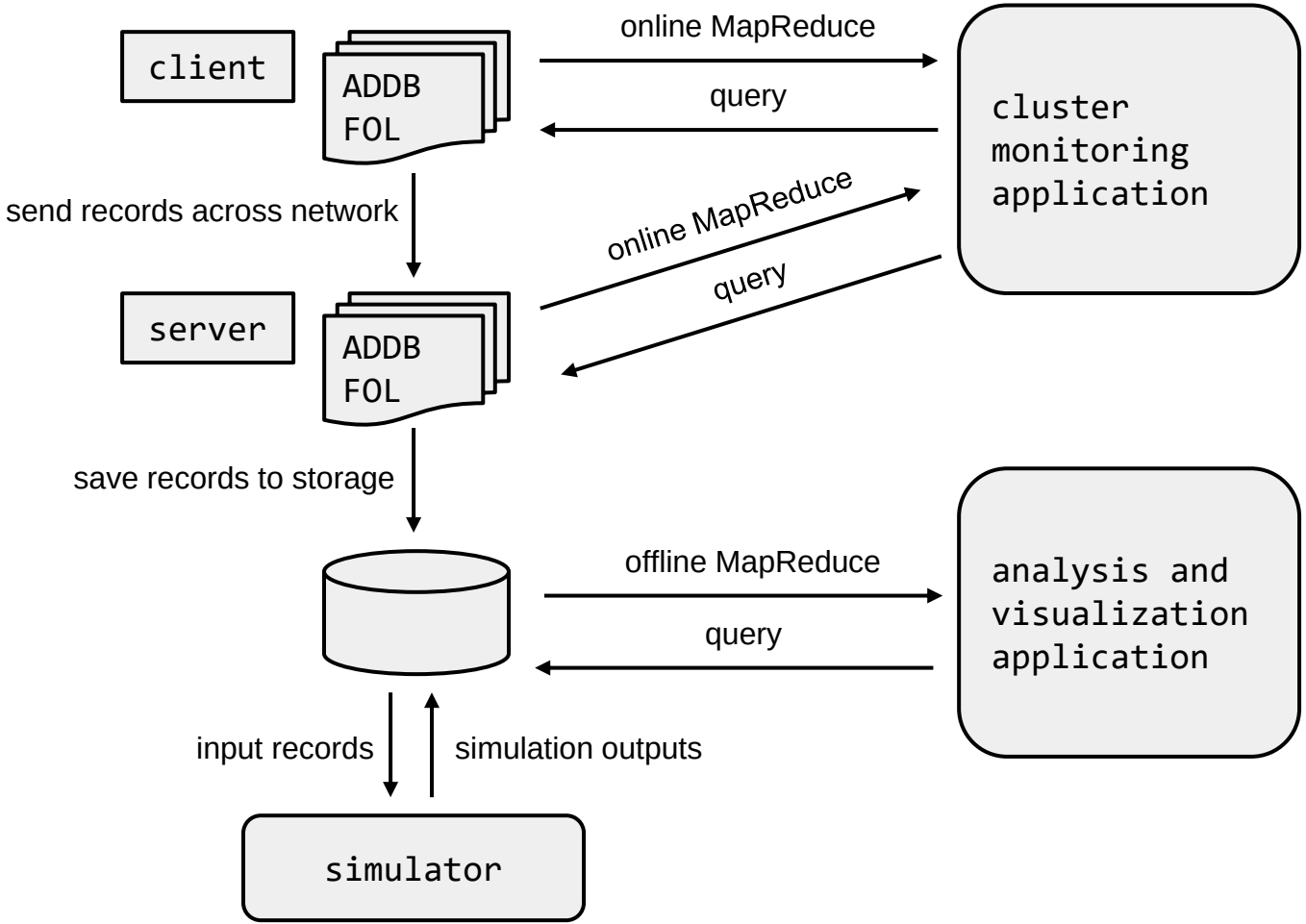
addb: state-machine transitions

```
* 2018-04-05-14:37:09.660378140 be-op/m0_be_op::bo_sm: M0_BOS_ACTIVE -[completed]-> M0_BOS_DONE
  nr: 27788 min: 0 max: 556380 avg: 785.763279 dev: 56005939.461453 datum: 0
  0 0: 25862 2066: 1138 4132: 309 6198: 98 8264: 61 10330: 67 12396: 68
    14462: 30 16528: 12 18594: 10 20660: 23 22726: 29 24792: 81
|         node             <5e341757d0cf46eb:92a6d6e991b46387>
|         pid              6627
|         locality         2
```

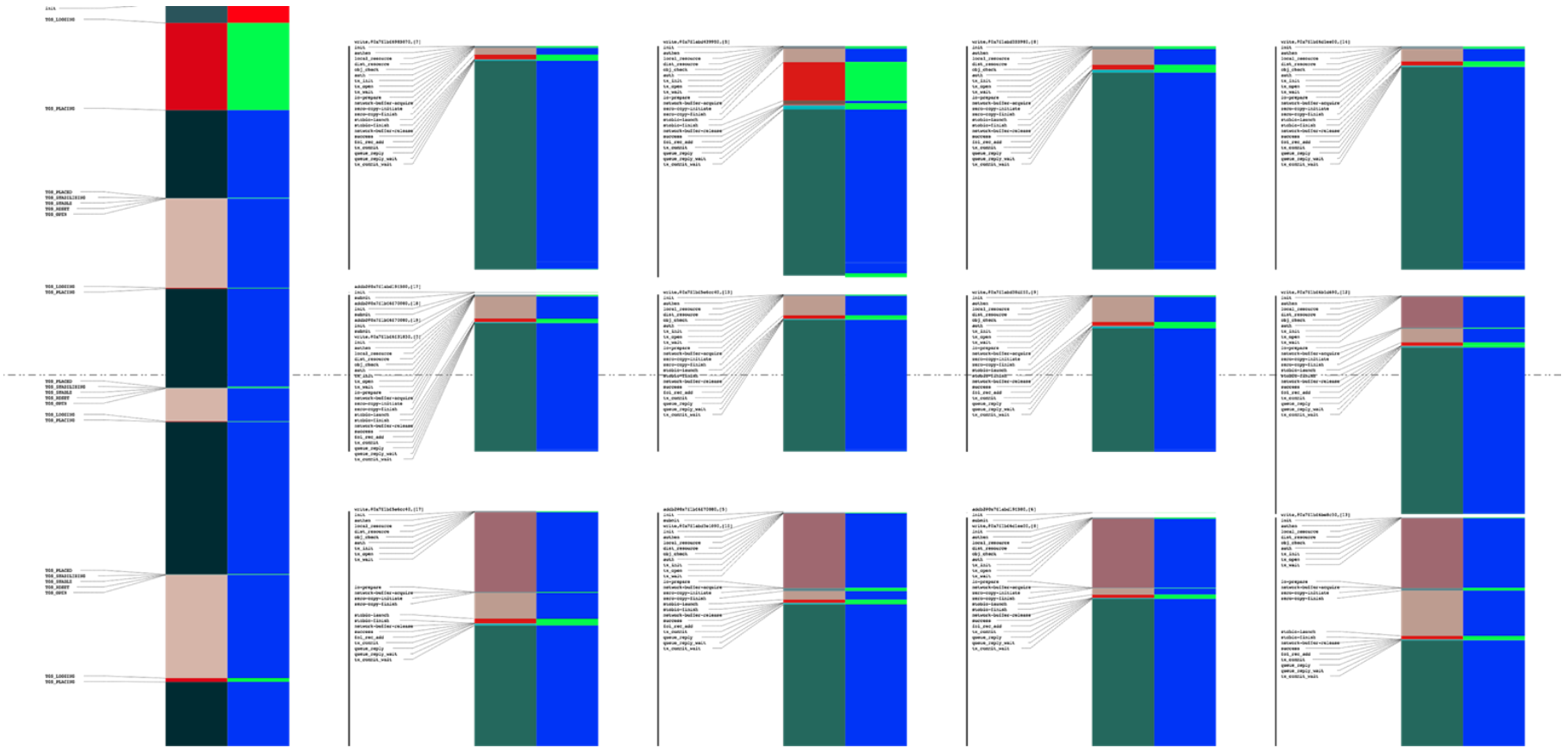
- request processing on clients and servers
- state machines
- state transition delays: in "binary microseconds", second >> 10

```
      :     0 |
    0 : 25862 | **************************
 2066 :  1138 | ************
 4132 :   309 | ***
 6198 :    98 | *
 8264 :    61 | *
10330 :    67 | *
12396 :    68 | *
14462 :    30 |
16528 :    12 |
18594 :    10 |
20660 :    23 |
22726 :    29 |
24792 :    81 | *
```

addb



addb



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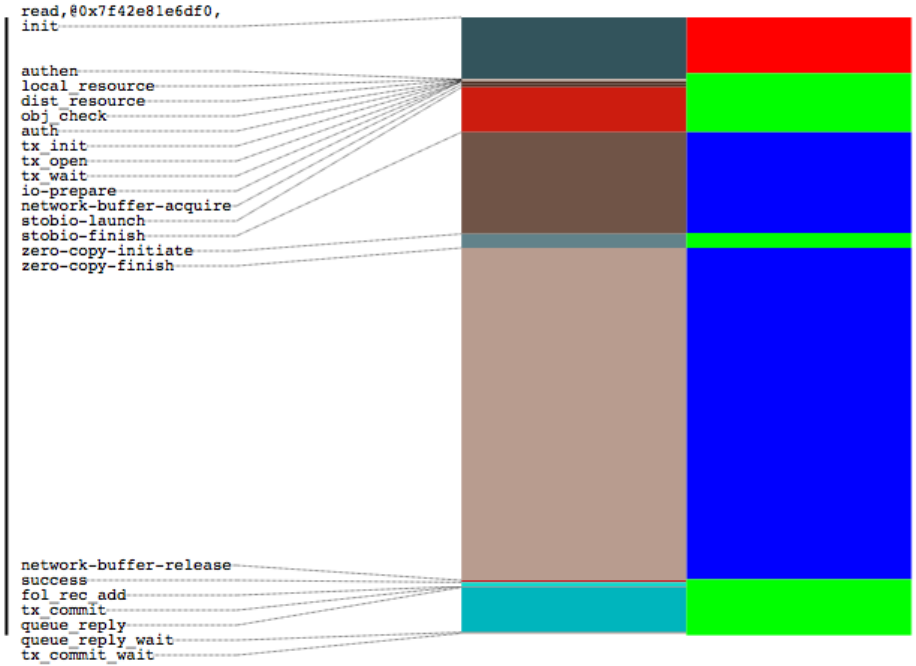
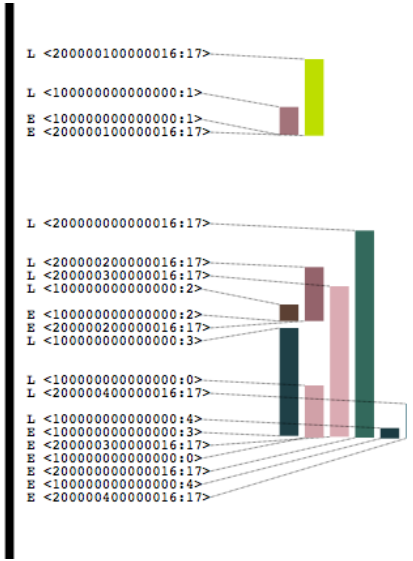
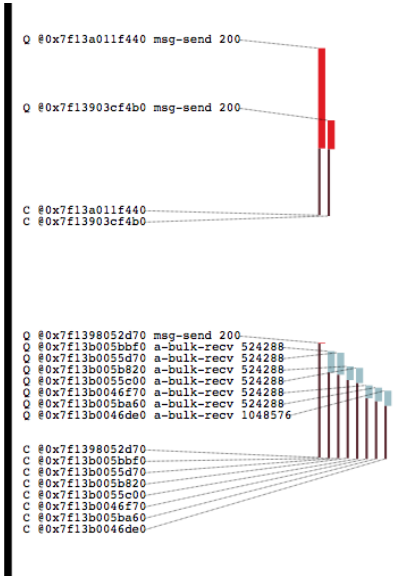
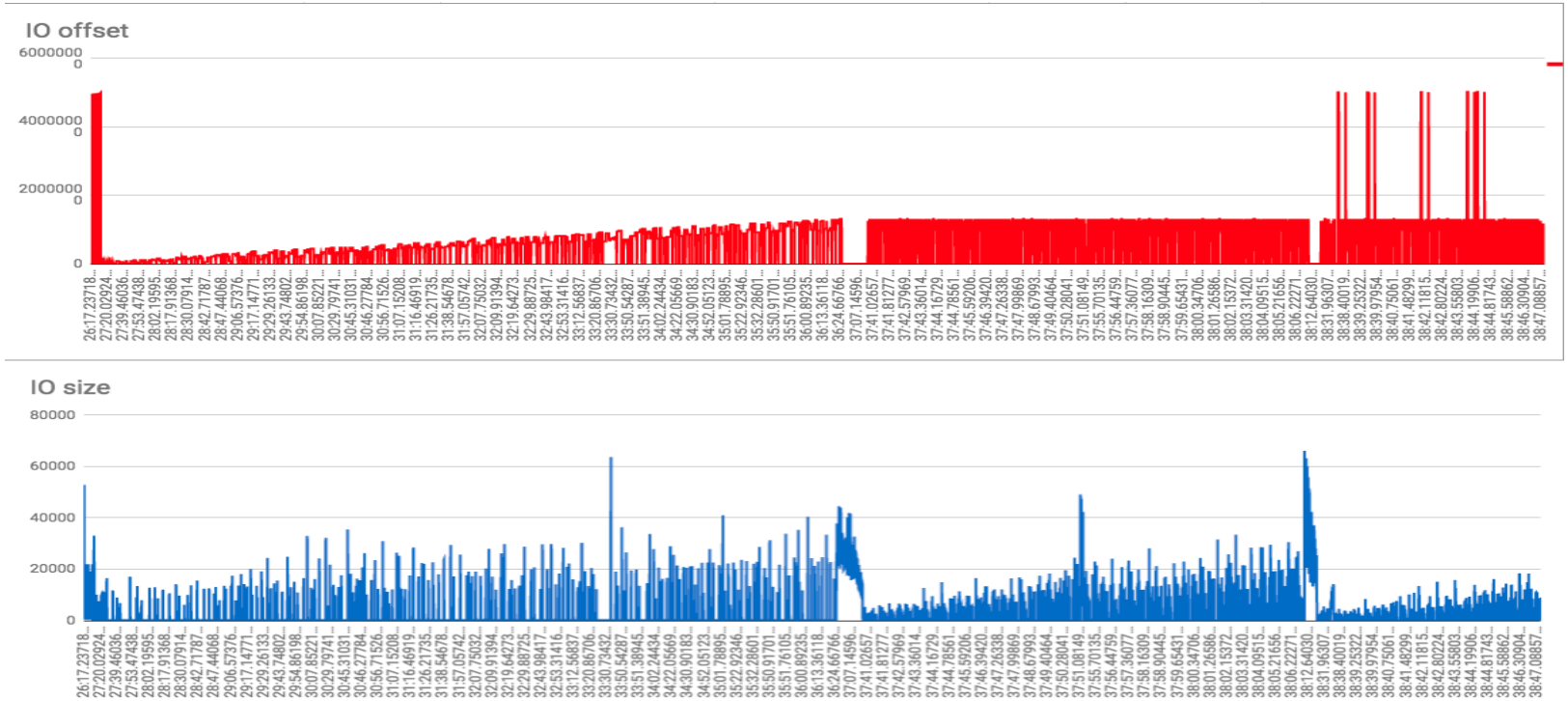






addb: ad hoc profiling

```
$ m0addb2dump ... | grep 'stob-io-launch' | awk '{print $2, $6, $12}'
```

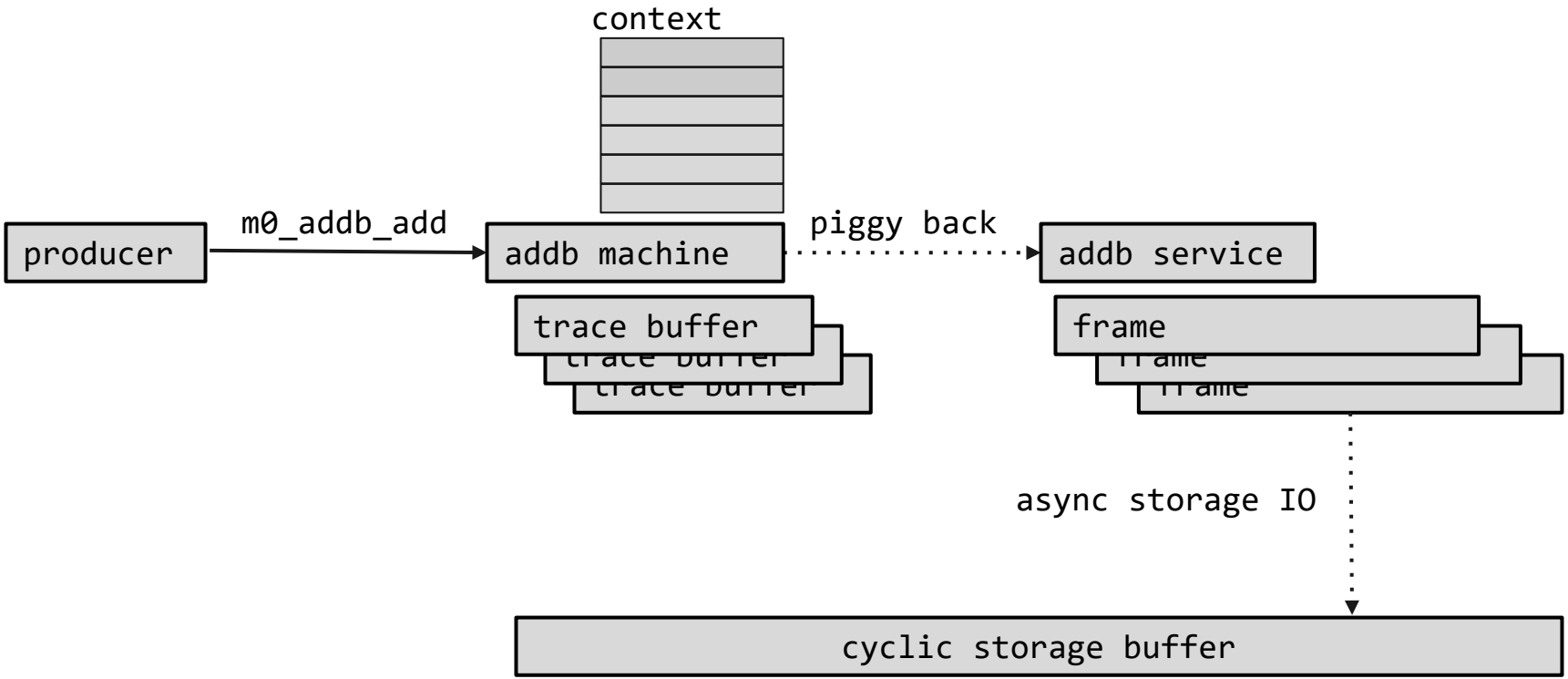


addb: interface

```
/**
 * Adds a label to the current context.
 *
 * @param id    - label identifier
 * @param n     - number of 64-bit values in label payload
 * @param value - payload
 */
void m0_addb_push(uint64_t id, int n, const uint64_t *value);
/**
 * Removes the top-most label in the current context stack.
 *
 * @param id - label identifier
 *
 * @pre "id" must the identifier of the top-most label.
 */
void m0_addb_pop(uint64_t id);
/**
 * Adds one-time measurement in the current context.
 *
 * @param id    - measurement identifier
 * @param n     - number of 64-bit values in measurement payload
 * @param value - payload
 */
void m0_addb_add(uint64_t id, int n, const uint64_t *value);
```

- very simple interface
- binary values only
- stack (LIFO) context
- context management is modular
- separate interface for sensors (not shown)
- usable from system and applications

addb: data flow



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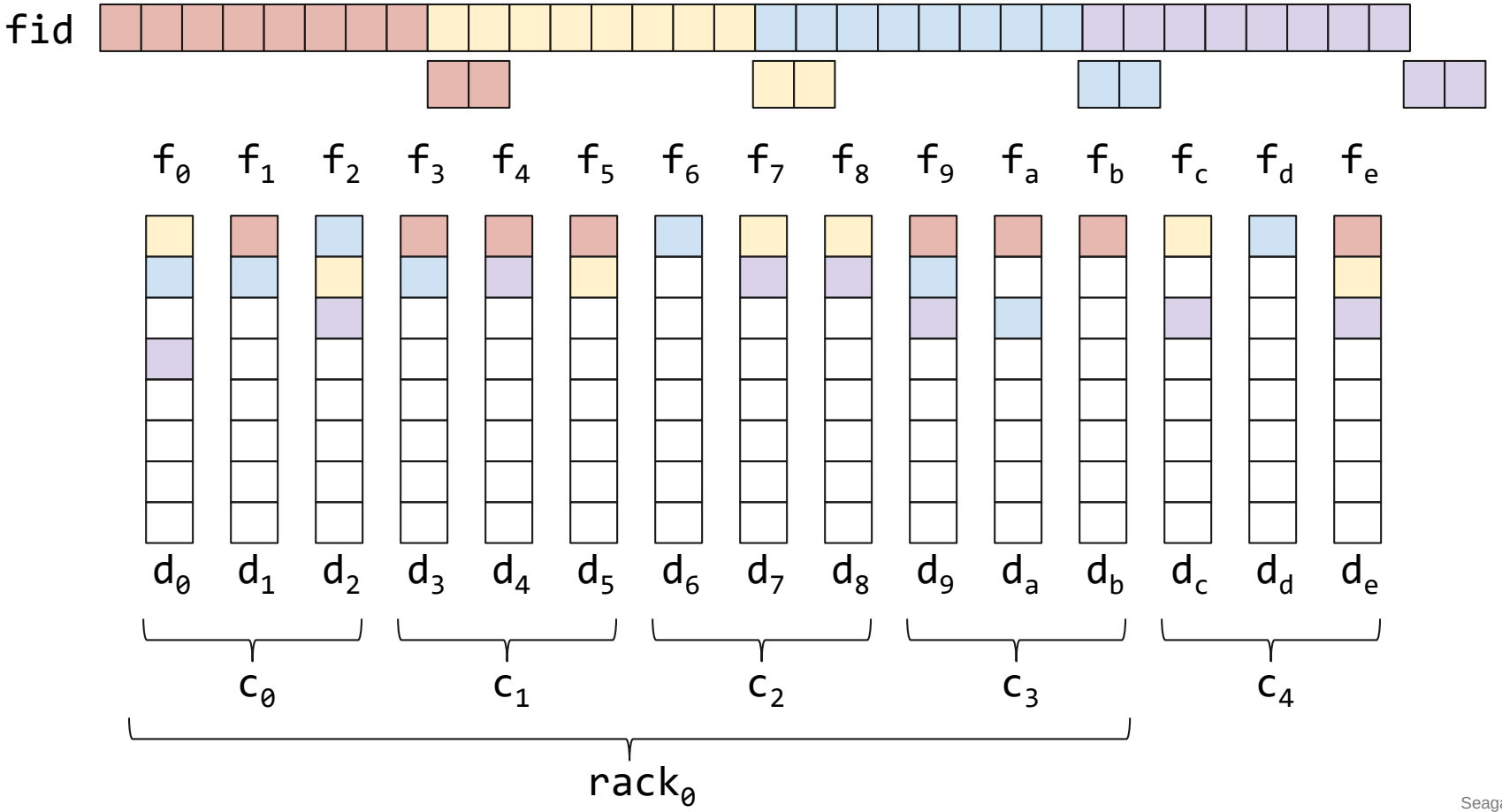
io: layout

- determines how an object is stored in underlying containers
- layouts for data and meta-data
- examples:
  - network striping with parity de-clustering (default)
  - compression
  - encryption
  - de-duplication
  - composite (NBA, small files, migration)

io: parity groups



io: permutations

0_0	0_1	0_2	0_3	0_4	0_p	0_q	1_0	1_1	1_2	1_3	1_4	1_p	1_q	2_0
2_1	2_2	2_3	2_4	2_p	2_q	3_0	3_1	3_2	3_3	3_4	3_p	3_q	4_0	4_1
4_2	4_3	4_4	4_p	4_q	5_0	5_1	5_2	5_3	5_4	5_p	5_q	6_0	6_1	6_2
6_3	6_4	6_p	6_q	7_0	7_1	7_2	7_3	7_4	7_p	7_q	8_0	8_1	8_2	8_3
8_4	8_p	8_q	9_0	9_1	9_2	9_3	9_4	9_p	9_q	10_0	10_1	10_2	10_3	10_4
10_p	10_q	11_0	11_1	11_2	11_3	11_4	11_p	11_q	12_0	12_1	12_2	12_3	12_4	12_p
12_q	13_0	13_1	13_2	13_3	13_4	13_p	13_q	14_0	14_1	14_2	14_3	14_4	14_p	14_q

PDRAID [15 (5+2+0)], 1 Tile

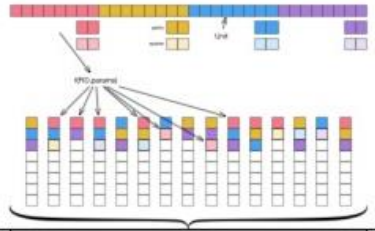
0_3	1_1	0_1	1_q	1_2	0_q	2_0	1_4	0_0	1_0	0_p	1_p	0_4	0_2	1_3
2_4	3_2	2_2	4_0	3_3	3_0	4_1	3_p	2_1	3_1	2_q	3_q	2_p	2_3	3_4
4_p	5_3	4_3	6_1	5_4	5_1	6_2	5_q	4_2	5_2	5_0	6_0	4_q	4_4	5_p
6_q	7_4	6_4	8_2	7_p	7_2	8_3	8_0	6_3	7_3	7_1	8_1	7_0	6_p	7_q
9_0	9_p	8_p	10_3	9_q	9_3	10_4	10_1	8_4	9_4	9_2	10_2	9_1	8_q	10_0
11_1	11_q	10_q	12_4	12_0	11_4	12_p	12_2	10_p	11_p	11_3	12_3	11_2	11_0	12_1
13_2	14_0	13_0	14_p	14_1	13_p	14_q	14_3	12_q	13_q	13_4	14_4	13_3	13_1	14_2

PDRAID [15 (5+2+0)], 1 Tile

layout: composite

Complex Layout

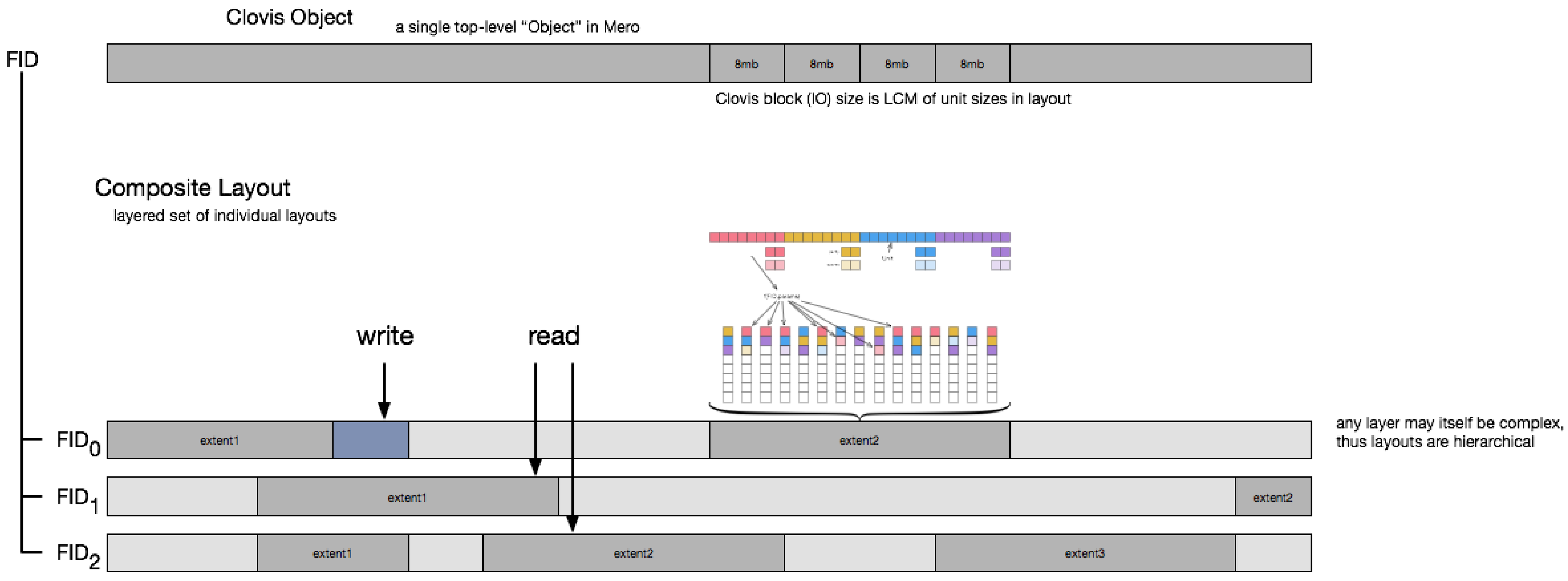
individual layout per extent



FID

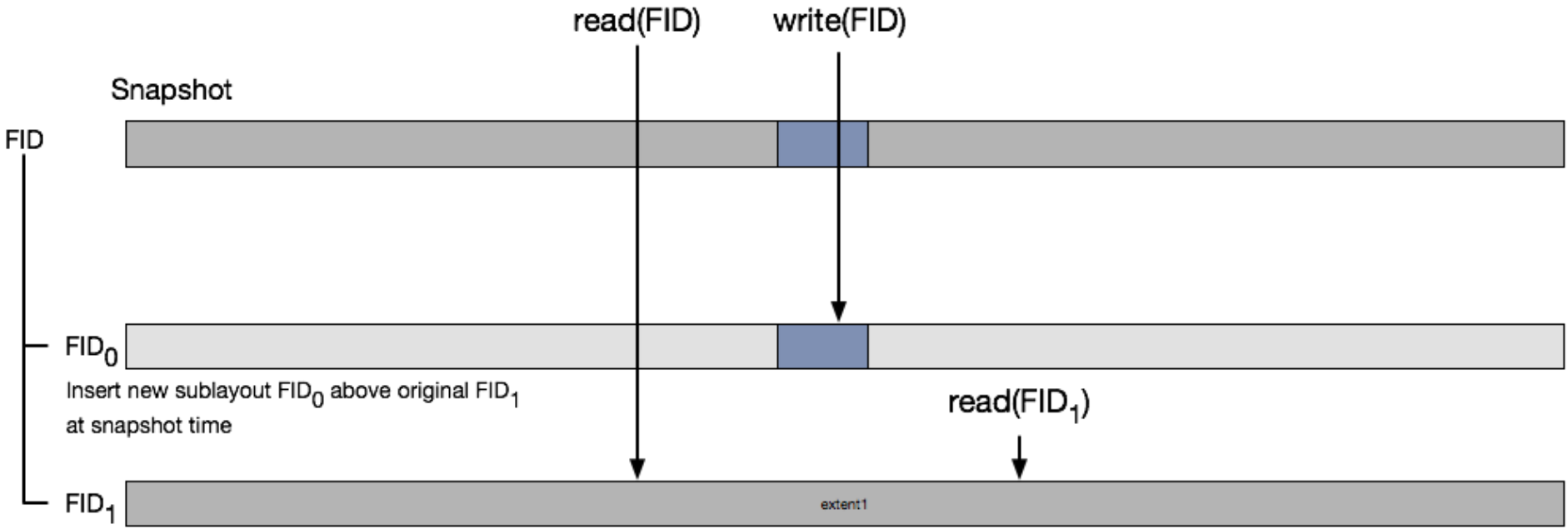
any layer may itself be complex, thus layouts are hierarchical

layout: composite



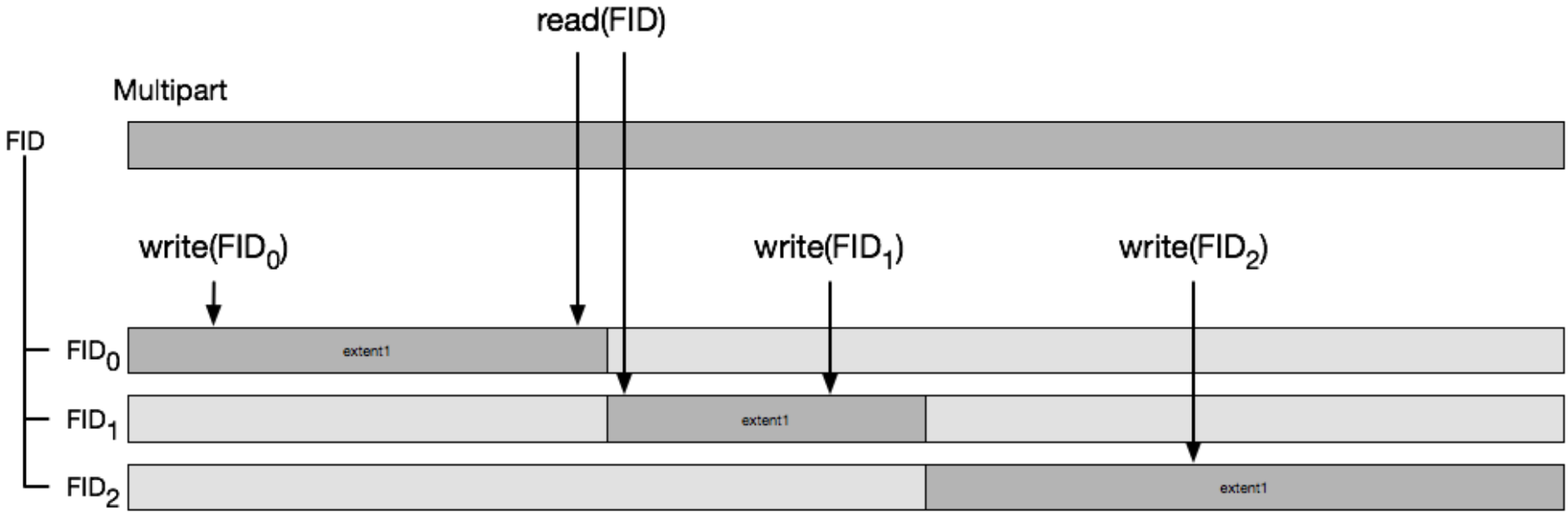
Reads and writes fall through to first layer with mapped extents. (Newly written blocks are added to read extents.) Layers can also be read/written directly using FID_{sub}

layout: composite: snapshot

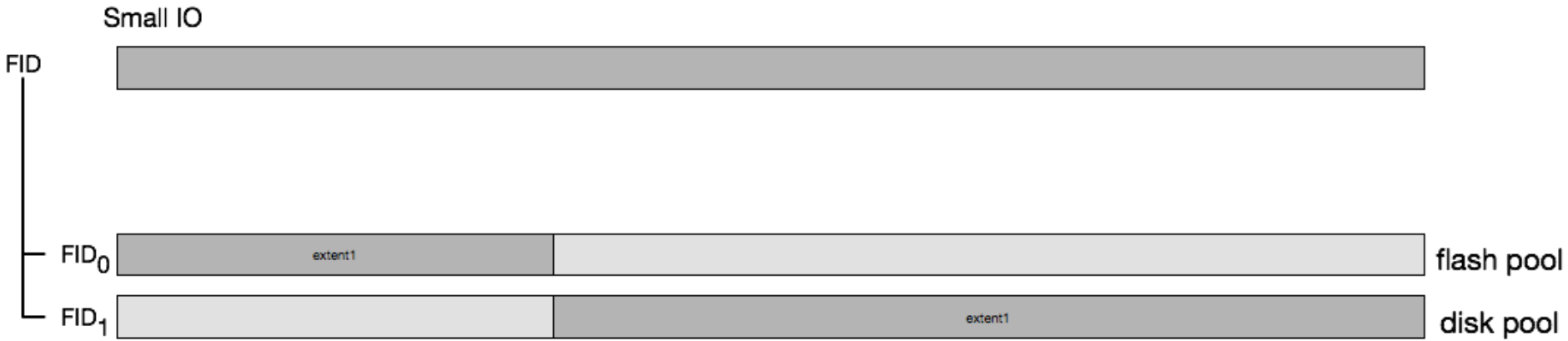


layout: composite: nba

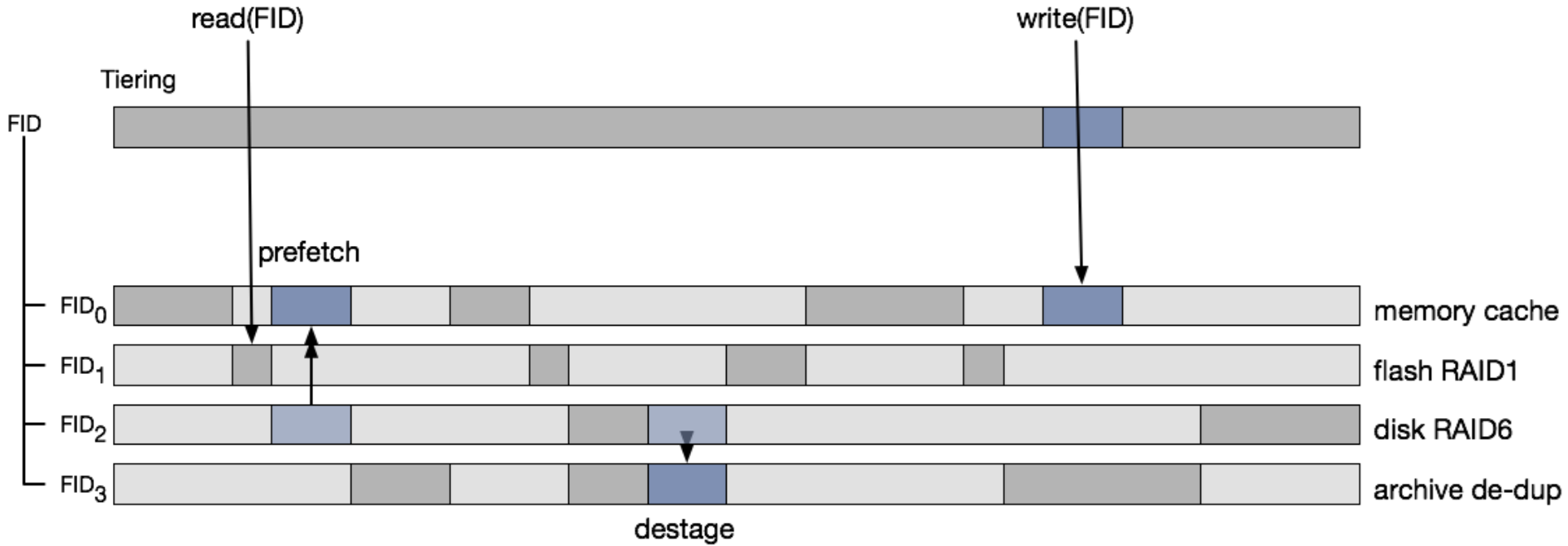
layout: composite: s3 partial upload



layout: composite: small files IO



layout: composite: HSM, tiering



components

- Motr client
- transactions (dtm)
- resource manager
- fdmi
- addb
- network raid, layouts
- **containers**
- function shipping
- lingua franca
- integrity checking
- meta-data back-end
- network, rpc, fop, HA
- fom, reqh
- device io (stob)
- network raid repair
- security

containers

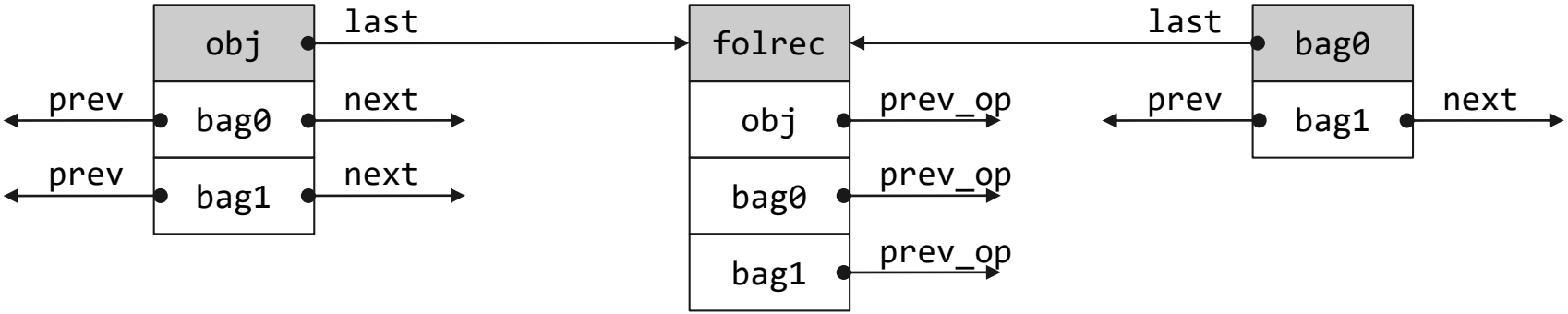
- container: an entity with a fid
- application fully controls containers
  - add an entity to a container;
  - remove an entity from a container;
  - list container elements;
  - execute bulk operation on container contents (compute-in-container)
- arbitrary "topology" (only restriction: no duplicates)

Non-properties:

- separate fid-space for contents
- strong isolation guarantees

containers implementation

- component containers, bag:
  - entities with fids,
  - lazily created when an entity is added to the container
- all local entities are linked together
- file operations log records (folrecs) for operations on container contents are linked



containers rationale

- efficiently identify containers to which an object belongs
- flexible container nesting
- concurrent mass-operations on containers
- container history is traceable
- fdmi filters on containers
- function shipping to a container

Don't have:

- ordering of container contents
- ordered enumeration
- "implicit" containers (*e.g.*, "all objects on this server")

containers use case

- application creates a container to track "entities of interest"
- entities are added to the container
- fdmi plugin is registered to receive notifications of all updates to the container
- examples:
  - hsm: fileset of hot objects
  - replication: source fileset

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function shipping

- move computation closer to data (compute-in-storage)
- reduce network transmission overhead
- application structuring mechanism
- bulk computation on all Motr client entities:
  - object: function on data blocks
  - index: function on key-value records
  - container: function on member fids
- built-in fault tolerance

function shipping implementation

- computations are first class Motr client entities
  - unique fid, globally addressable
  - registered dynamically by an application
- low level trusted mechanism:
  - dynamically load shared library into Motr service process
  - invoke computations remotely, argument-result passing
- untrusted mechanism:
  - run untrusted code (*e.g.*, Python) in a separate address space
- client uses layouts to start execution and recover from failures

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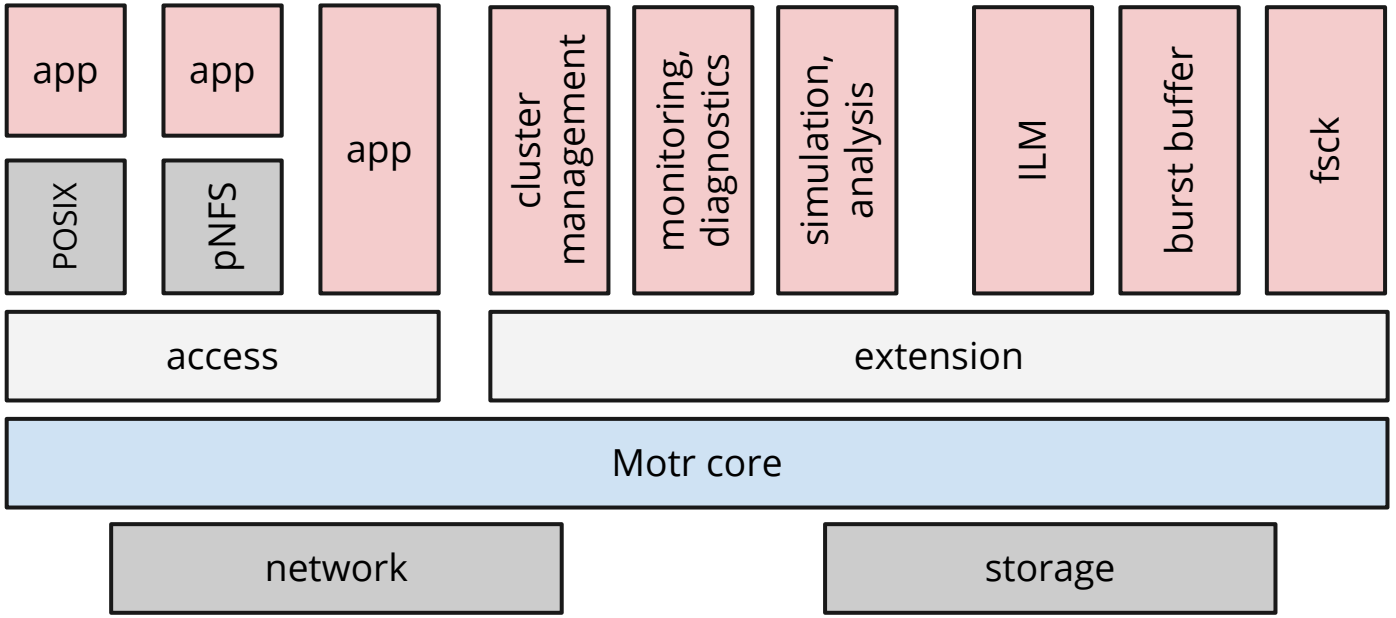
lingua franca



Multiple front-ends:

interoperability, common meta-data mechanism

lingua franca

- POSIX file system: *via* pNFS
  - straightforward semantics
  - concurrency:
    - concurrent reads
    - one writer
    - concurrent writers
- POSIX file system: *via* S3
  - interpret pathname as an URL (object key)
  - mapping of security and ownership attributes
- S3: *via* POSIX: parse URL as a pathname
- POSIX file system: *via* HDF5

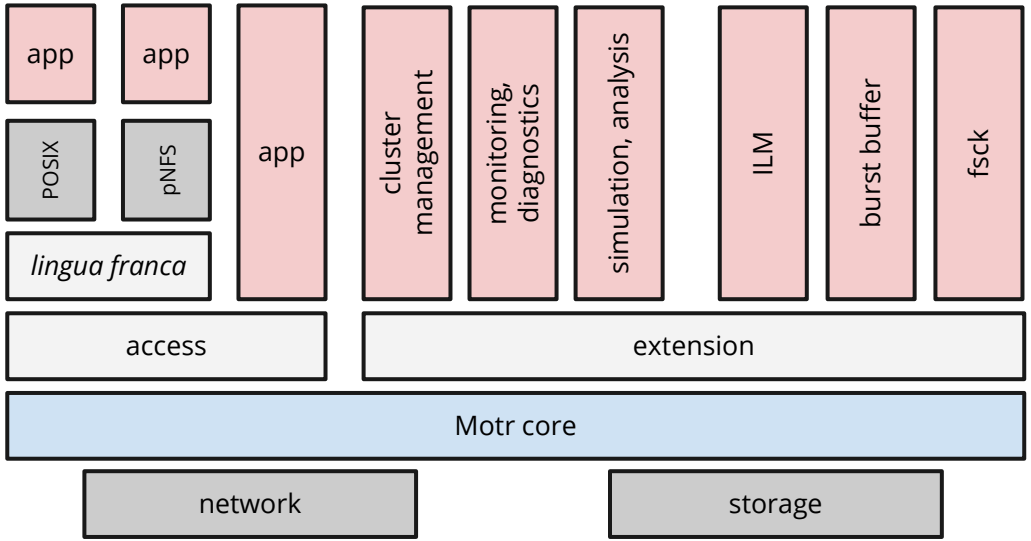
lingua franca

- S3 object: "blue_bucket/finance-9a84c723ee89f4b723b46cc5f1642b3"
- mount S3 store as POSIX

```
$   cd blue_bucket
$   ls -l finance-9a84c723ee8*
-rw------- 1 satoshi satoshi 285 January 03 2009 finance-9a84c723ee89f4b723b46cc5f1642b3
```

- enumerate and locate objects
- access attributes
  - system attributes: layout, containers;
  - common attributes: size;
  - front-end specific attributes: POSIX nlink
- efficiency: remote meta-data lookups are expensive

lingua franca



POSIX, pNFS, CIFS, S3/SWIFT, MPI Object IO, HDF5, MySQL, block device

lingua franca implementation

- what are the *entities* managed by an FE?
- how entities are named?
- how entities are organised: tree, graph, array?
- how attributes are associated with entities?
  - different FEs have different sets of native attributes
  - an FE wants to add attributes to foreign entities
  - an FE wants to interpret foreign attributes
  - some attributes are shared by multiple FEs
- core system has its own attributes

lingua franca implementation

- a domain of files (entities), a file identified by a 128-bit *fid*
- two indices:
  - name-space (ns): records file attributes
  - object index (oi): maps from the file fid to all its names

ns index structure:

key	value
FRONTENDID+FNAME+ATTRCLASS+ATTRID	attribute value

oi index structure:

FID+FRONTENDID+FNAMEID	FRONTENDID+FNAME

lingua franca implementation: S3

- `FRONTENDID: 3`
- `ATTRCLASS: 3`
- `FNAME: Object-URI: bucketname+NUL+object_key+NUL`

object: "app_bucket/statement.xls", fid `0x60000:0x17ae76d0f`

ns index:

key	value	comment
`3app_bucket\0statement.xls\0!fid`	`0x60000:0x17ae76d0f`	the fid of the object "`statement.xls`"
`3app_bucket\0statement.xls\03content-length`	`3201526`	object size in bytes
`3app_bucket\0statement.xls\03content-md5`	`0x62ae2f12137738a9:0x173f5224f81446aa`	md5 checksum
`3app_bucket\0statement.xls\03last-modified`	`2017-04-26-15:29:30.85267`	last modification timestamp
`3app_bucket\0statement.xls\03...`		other S3 attributes

lingua franca implementation: S3

object: "app_bucket/statement.xls", fid `0x60000:0x17ae76d0f`

oi index:

key	value	comment
`3:0000000000060000:0000000017ae76d0:30`	`3app_bucket\0statement.xls`	name of the object

lingua franca implementation: POSIX

- `FRONTENDID: P`
- `ATTRCLASS: P`
- `FNAME: parent_directory_fid+name_in_the_directory`

object: "/etc/passwd", fid `0x70000:0x322e1673fd`

parent directory: "/etc", fid: `0x70000:0x18203a6485`

ns index:

key	value	comment
`P:70000:18203a6485:passwd!fid`	`0x70000:0x322e1673fd`	the fid of the object "`/etc/passwd`"
`P:70000:18203a6485:passwdPsize`	`16523`	file size
`P:70000:18203a6485:passwdPatime`	`2017-04-26-15:29:30.85267`	access time
`P:70000:18203a6485:passwdP...`		other POSIX attributes

lingua franca implementation: POSIX

object: "/etc/passwd", fid `0x70000:0x322e1673fd`

oi index:

key	value	comment
`P:0000000000070000:0x000000322e1673fd:P0`	`P:70000:18203a6485:passwd`	name of the object
`P:0000000000070000:0x000000322e1673fd:P1`	`P:70000:18203a6485:passwd.1`	another name: hard-link

```
# ln /etc/passwd /etc/passwd.1
```

lingua franca implementation: features

- each attribute is a separate key-value pair: flexibility
- new attributes can be added to existing files
  - without breaking compatibility
- attributes can be enumerated (NEXT operation)
  - an FE can selectively handle attributes it understands
- contents of a directory can be enumerated
- new names can be added to a file

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integrity checking

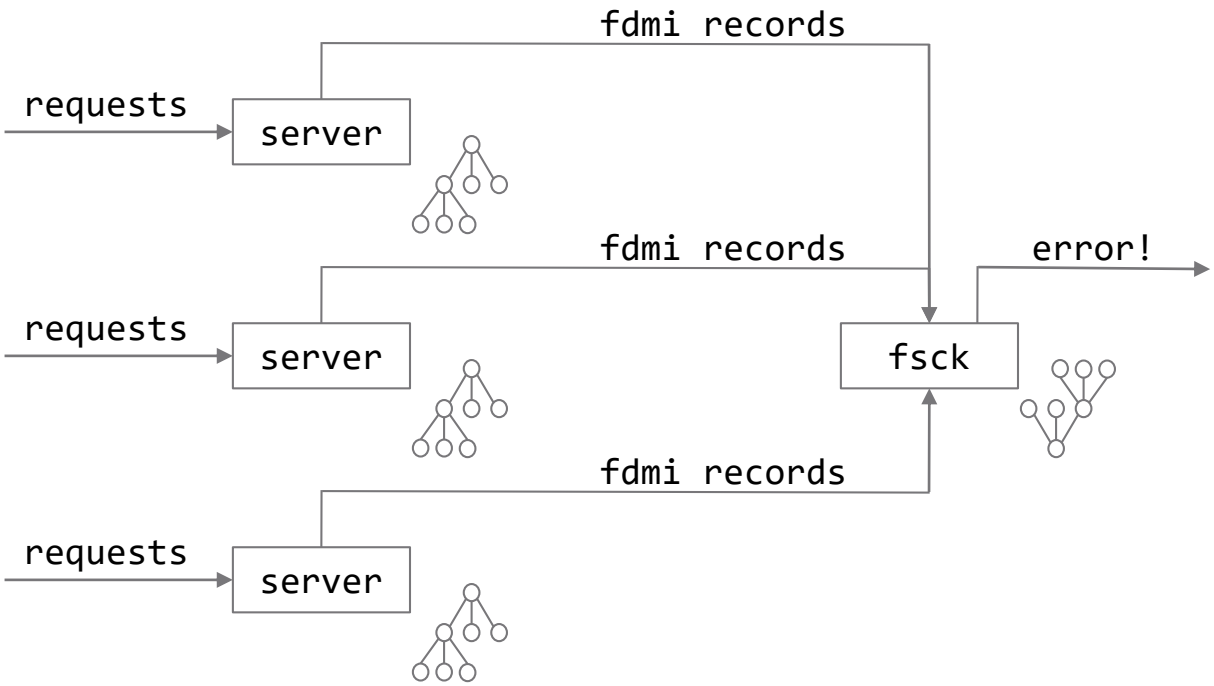
- redundancy, fancy metadata: not an answer (has been tried)
  - bugs (more important over time)
  - recovery from catastrophic failures
- traditional fsck
  - not distributed
  - specific to particular meta-data format
  - does not scale
    - time
    - space

integrity checking

- need scalable integrity checking
- run it all the time
- on dedicated separate nodes (horizontal scalability)
  - maintain redundant "inverse" meta-data
  - update meta-data to match system evolution (fdmi)
  - detect inconsistencies
  - report, recover from redundancy
  - recover catastrophic failures
- usual redundancy: parity, checksums, background scrub
- fdmi: transactional coherence with the main state

- parallel programming

integrity checking



inverse meta-data

- block allocation
- pdclust structure
- key distribution
- b-tree structure
- application specific invariants
  - POSIX tree
  - hdf5

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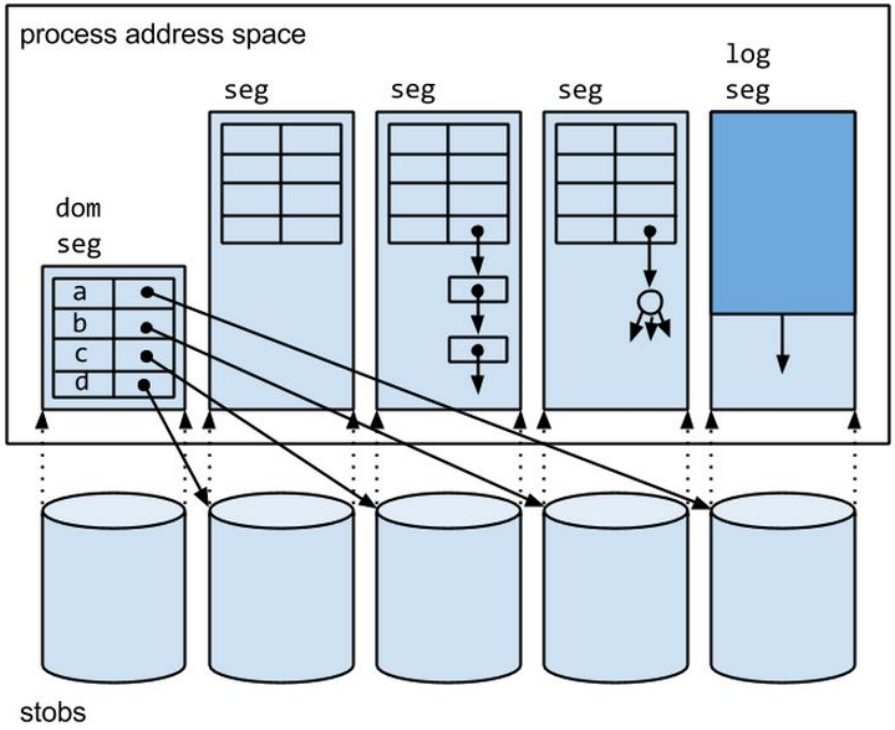
backend

- segment
- transaction
- domain
- container
- WAL
- redo-only
- allocator
- btree



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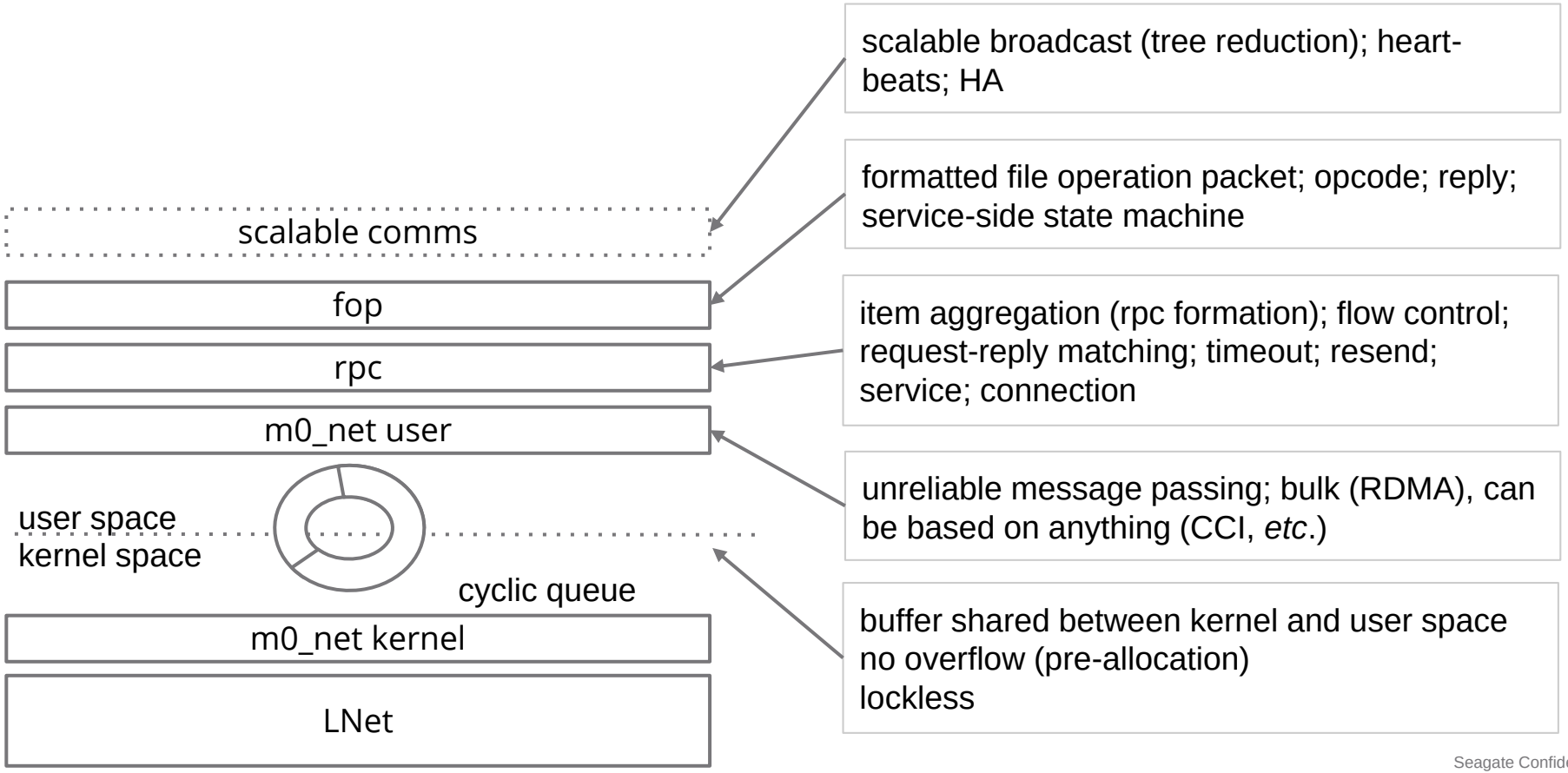
comm

- network: LNet, 0-copy, unreliable message passing
- rpc
  - message packing (formation),
  - request-reply semantics
  - retransmit
- xcode: serialisation library
- fop: operation packet
- *reduce-broadcast*
  - communication and aggregation tree
  - provided by HA

comm



comm: xcode

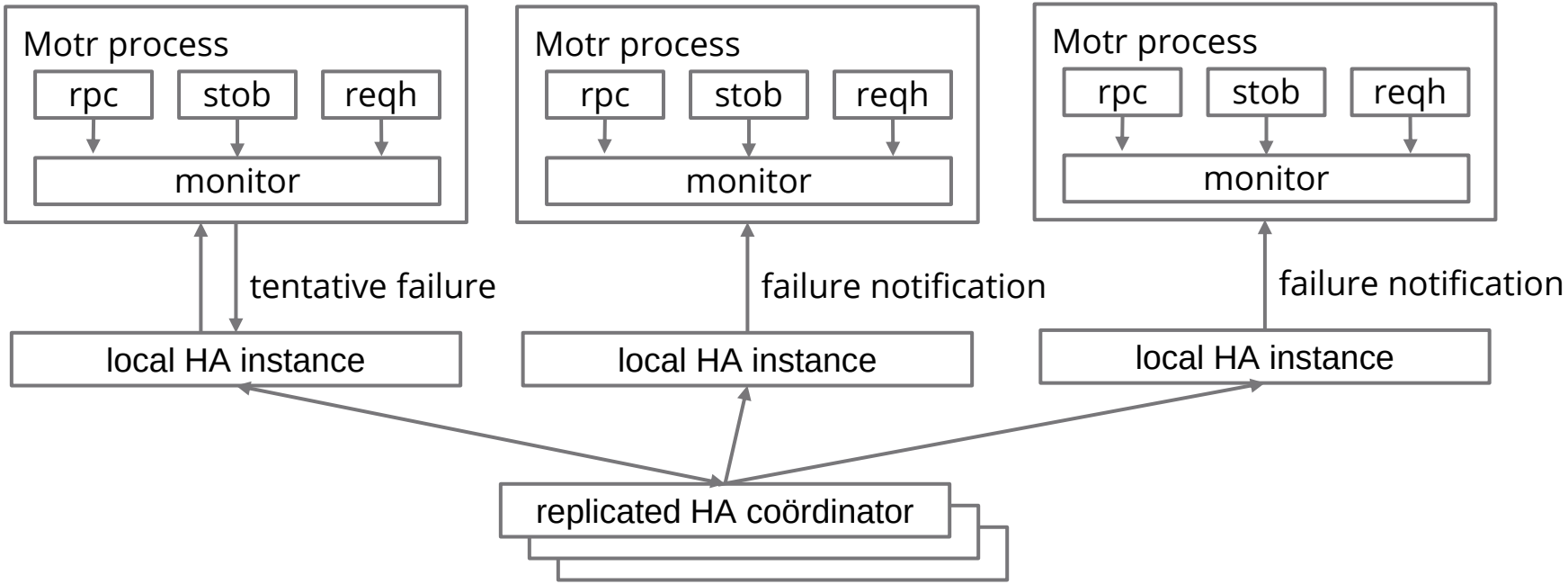
- a library adding a (modest) amount of reflection to C
- annotate header file foo.h
- gccxml: C parser
- generate foo_xc.h, foo_xc.c

```
struct m0_foo {
        uint32_t       f_nr;
        struct m0_bar *f_bar;
} M0_XCA_RECORD;
```

```
static struct m0_xcode_type m0_foo_xc = {
        .xct_name   = "m0_foo",
        .xct_sizeof = sizeof (struct m0_foo),
        .xct_children = {
                [0] = { "f_nr",  &M0_XT_U32, offsetof(struct m0_foo, f_nr) },
                [1] = { "f_bar", &m0_bar_xc, offsetof(struct m0_foo, f_bar) }
};
```

- m0_xcode_{en,de}code(), m0_xcode_{find,print,read}()

comm: HA



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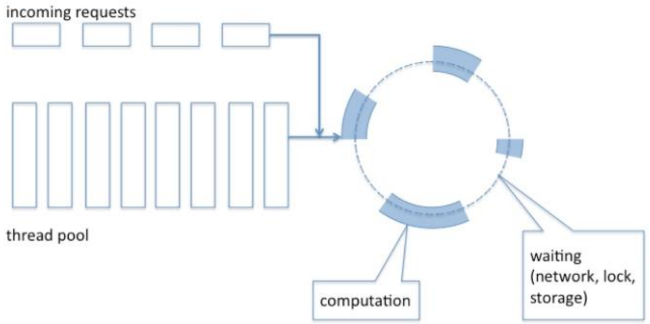
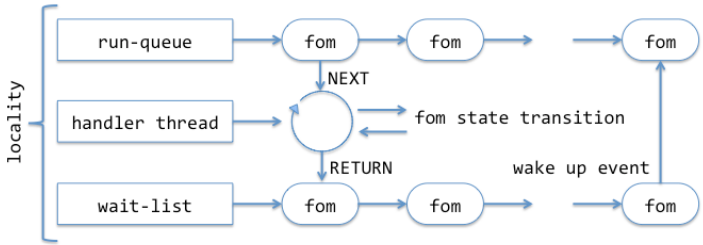
fom

- thread-per-request:
  - multiple cores, NUMA,
  - locking,
  - cache ping-pong,
  - c10K, many threads
- reqh:
  - thread per core
  - non-blocking scheduler
  - locality of reference
  - load balancing
  - long-term scheduling





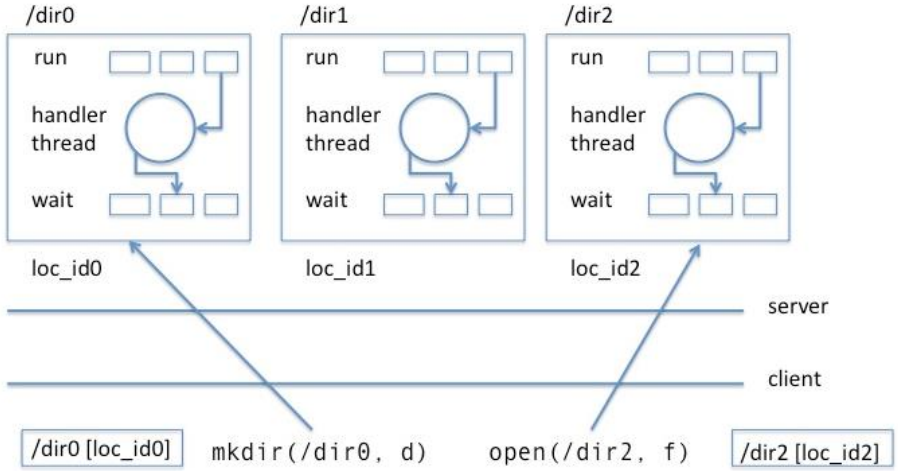
fom: request handler

```
while (!locality->shutdown) {
        while (have_work) {
                network_drain();
                stob_drain();
                fom_transition();
        }
        wait_for_work();
}
```

```
fom_transition(locality *l) {
        for_each(fom, l->run_queue) {
                good = goodness(l, fom);
                if (good > max_goodness) {
                        best = fom;
                        max_goodness =
fom_good;
                }
        }
        best->state(); /* state transition */
}
```

```
goodness(locality *l, fom *f) {
        if (abs(fom->next_block_nr, l->elevator_pos) < threshold)
                result += 1;
        if (l->pending_rpc[fom->next_nid] > 0)
                result += 1;
        result += take_deadline_into_account(l, f);
        result += take_priority_into_account(l, f);
        ...
}
```

fom: load balancing



- each locality is a small server
- clients talk to particular locality, using opaque identifier
- change identifier for load-balancing

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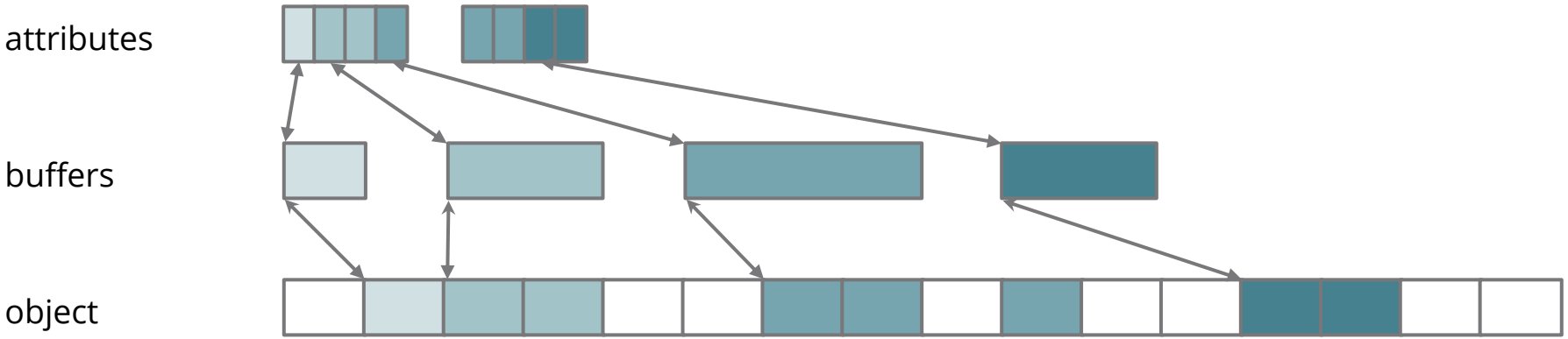
- **device io (stob)**
- network raid repair
- security

stob

- array of data-blocks, [0, 2^{64}), initially a hole
- create, delete, read, write, alloc, free operations
- IO at block granularity
- no usual meta-data (attributes, *etc*.)
- block attributes can be used for checksums, encryption keys, hash fingerprints
- scatter-gather-scatter operations: data and block attributes

stob: IO



stob: implementations

- linuxstob (*aka* devstob)
  - stob = file
  - aio
- adstob (allocation data stob)
  - multiple stobs stored in a backend stob
  - block allocator balloc
    - based on ext4 mballoc

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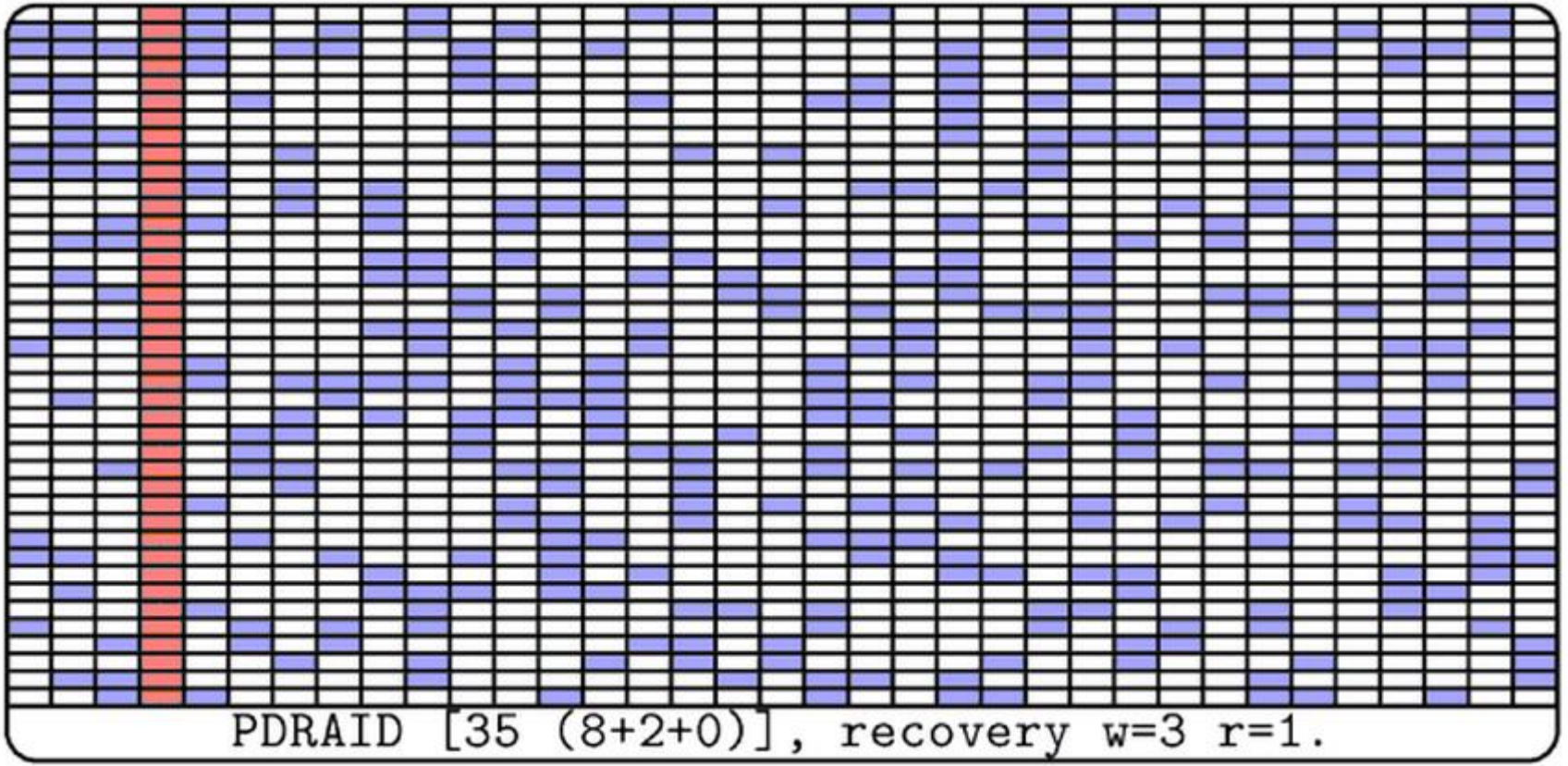
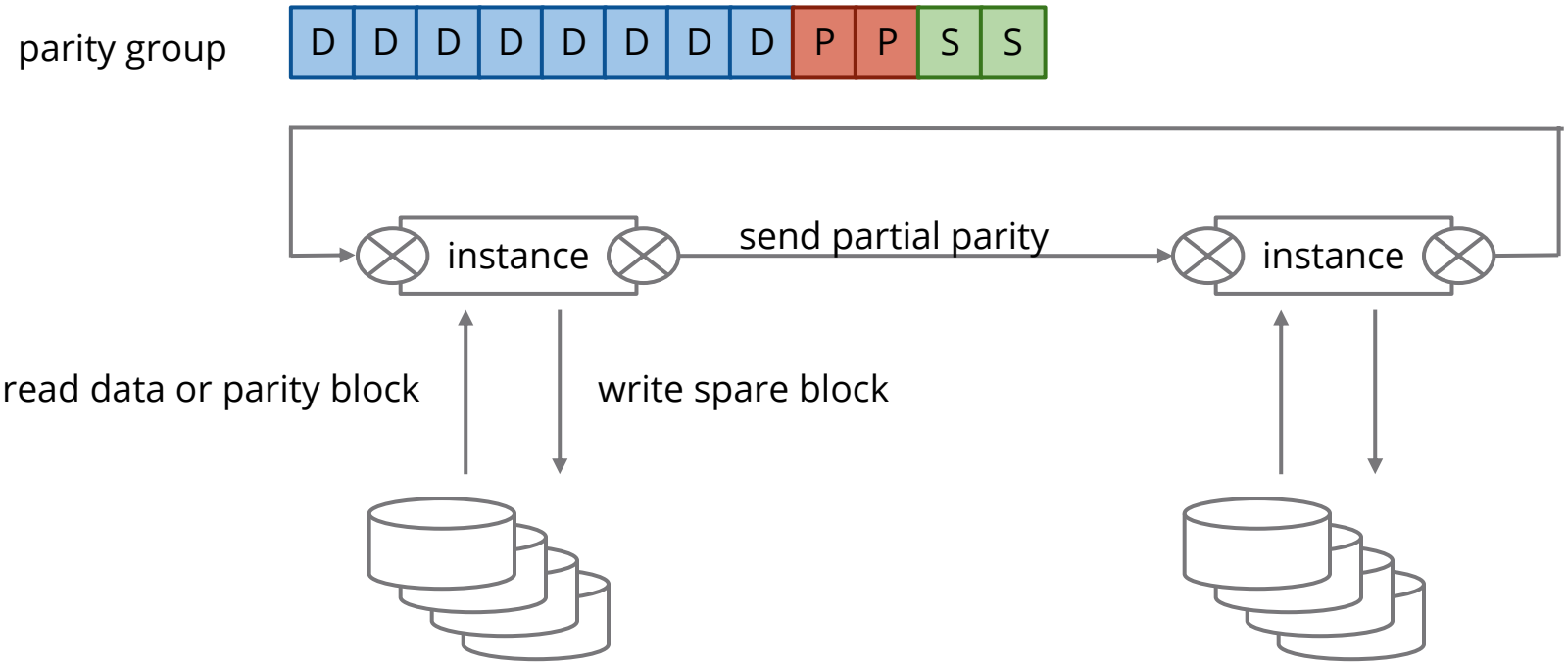
sns

- guaranteed IO performance during repair
- fast repair
- copy machine
- repair
- rebalance
- pool
- *flattening*

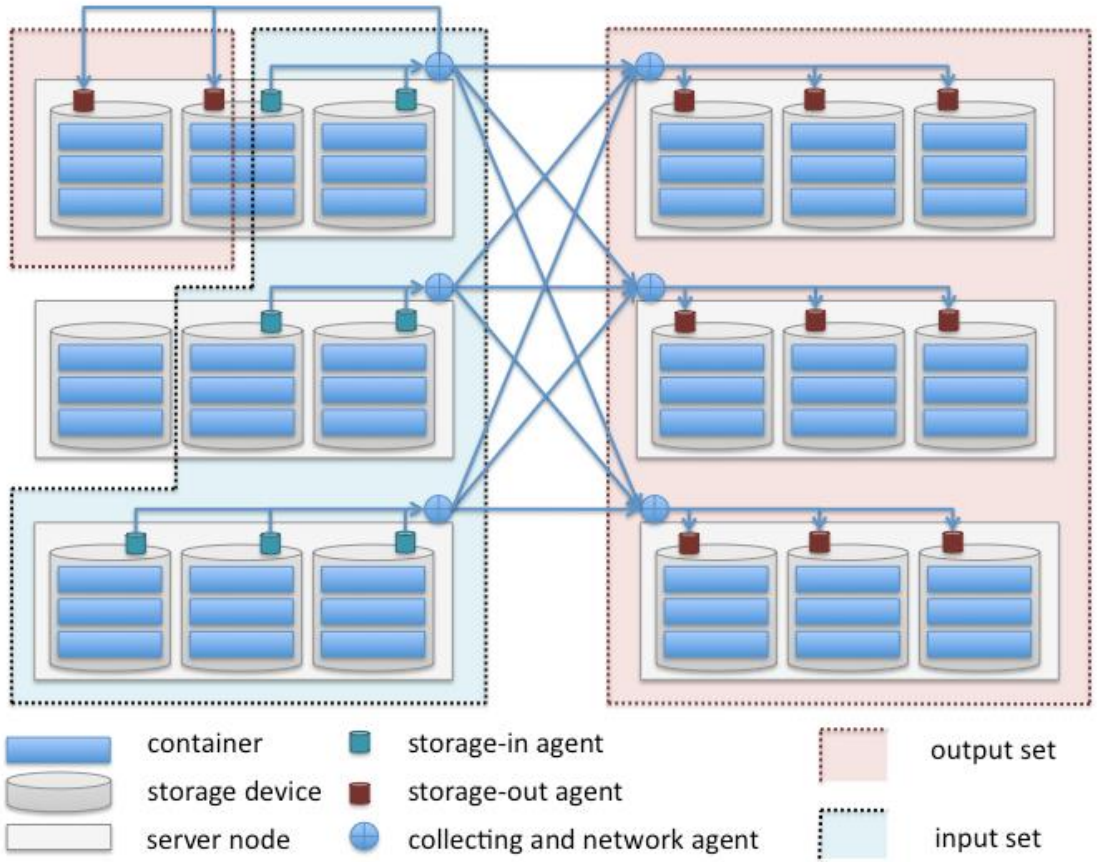
sns: repair



sns: copy machine

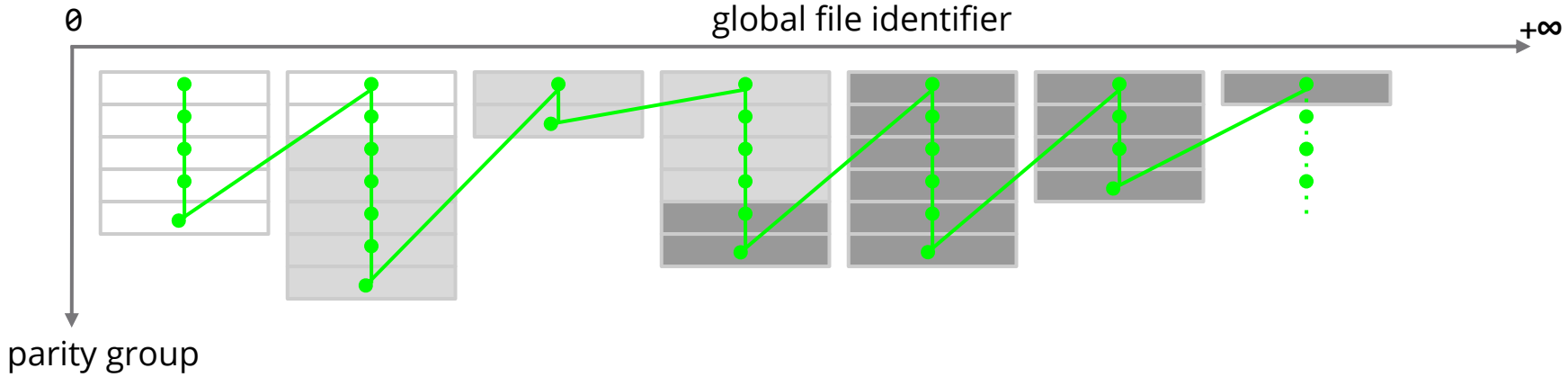


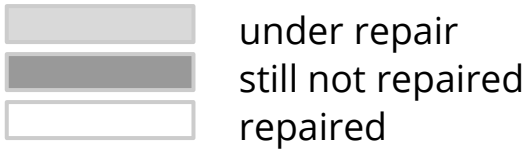
sns: network



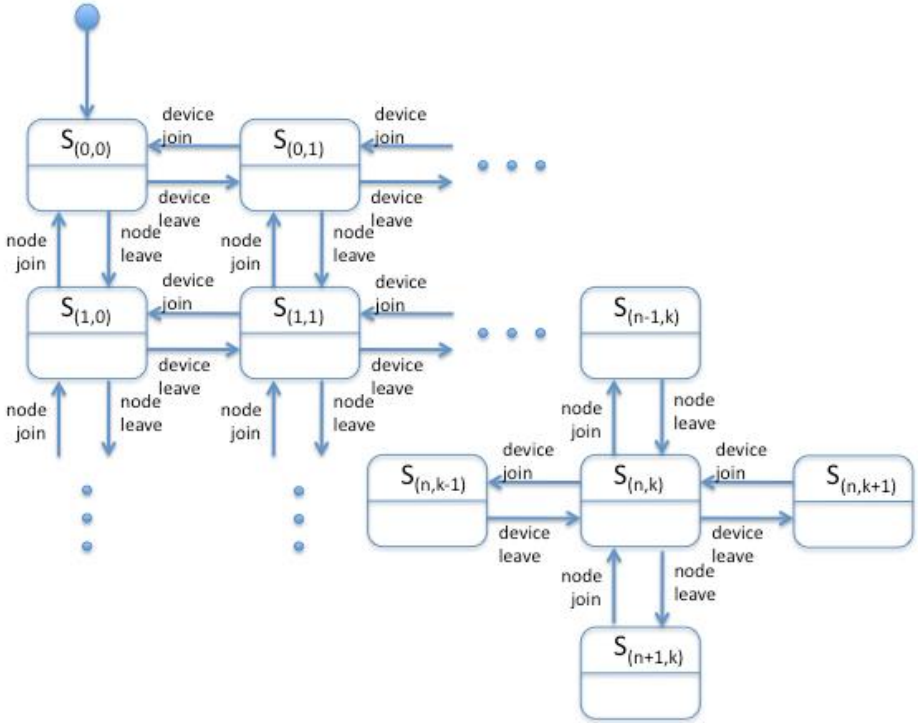
sns: coördination

copy machine sliding window

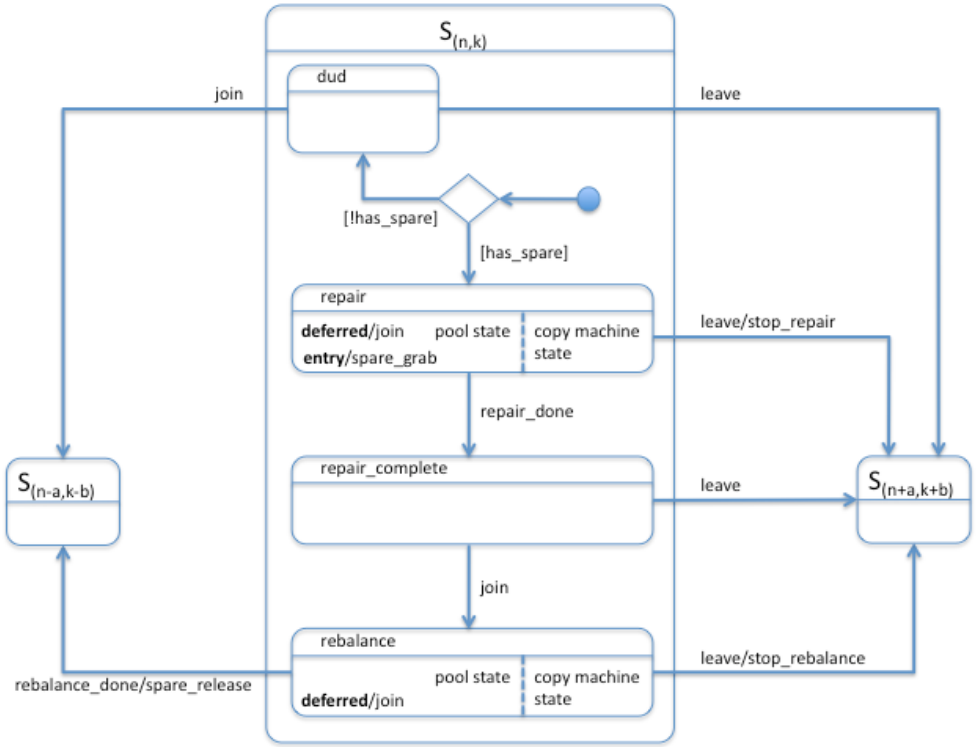




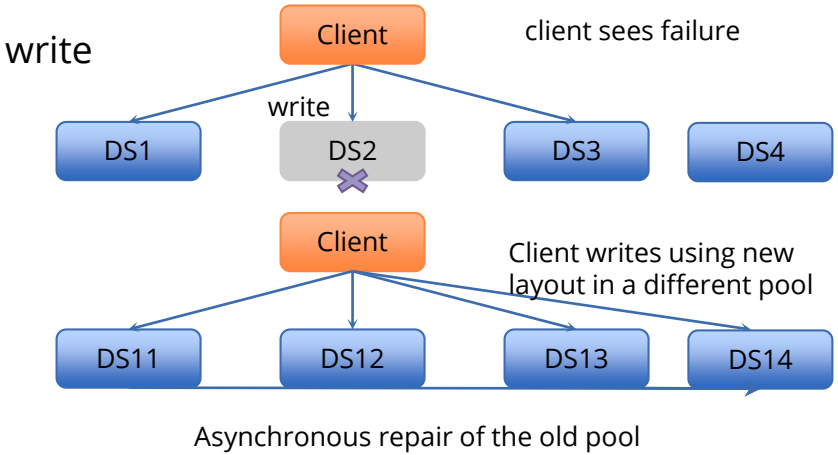
sns: failure state machine

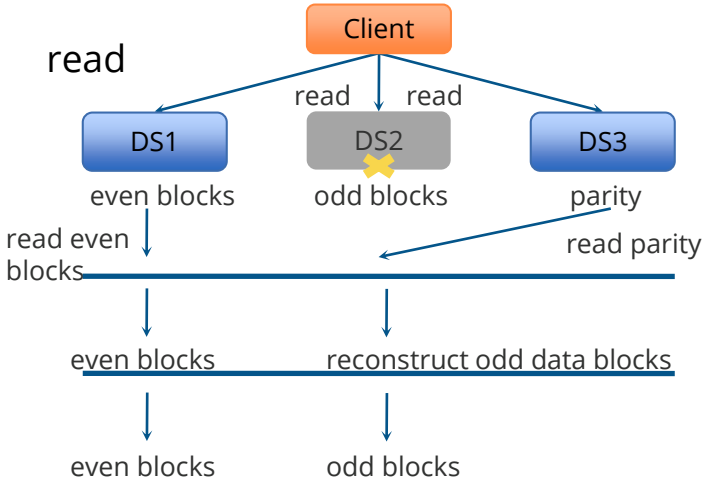


sns: failure in detail



sns: nba





- client senses failure by timeout, notifies HA
- how new layout is selected? Layout formula
- composite layout with list of extents
- flattening: restore simple layout

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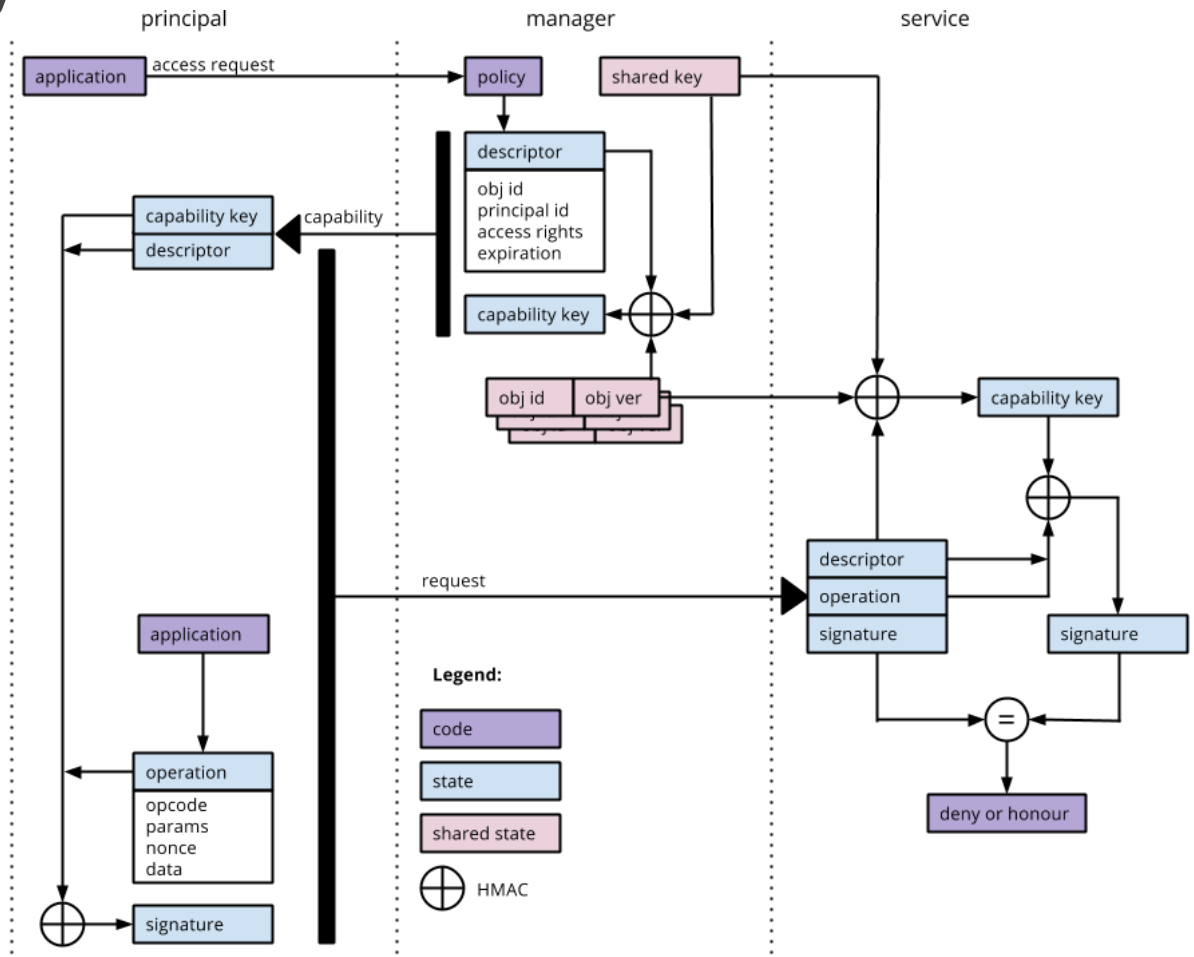
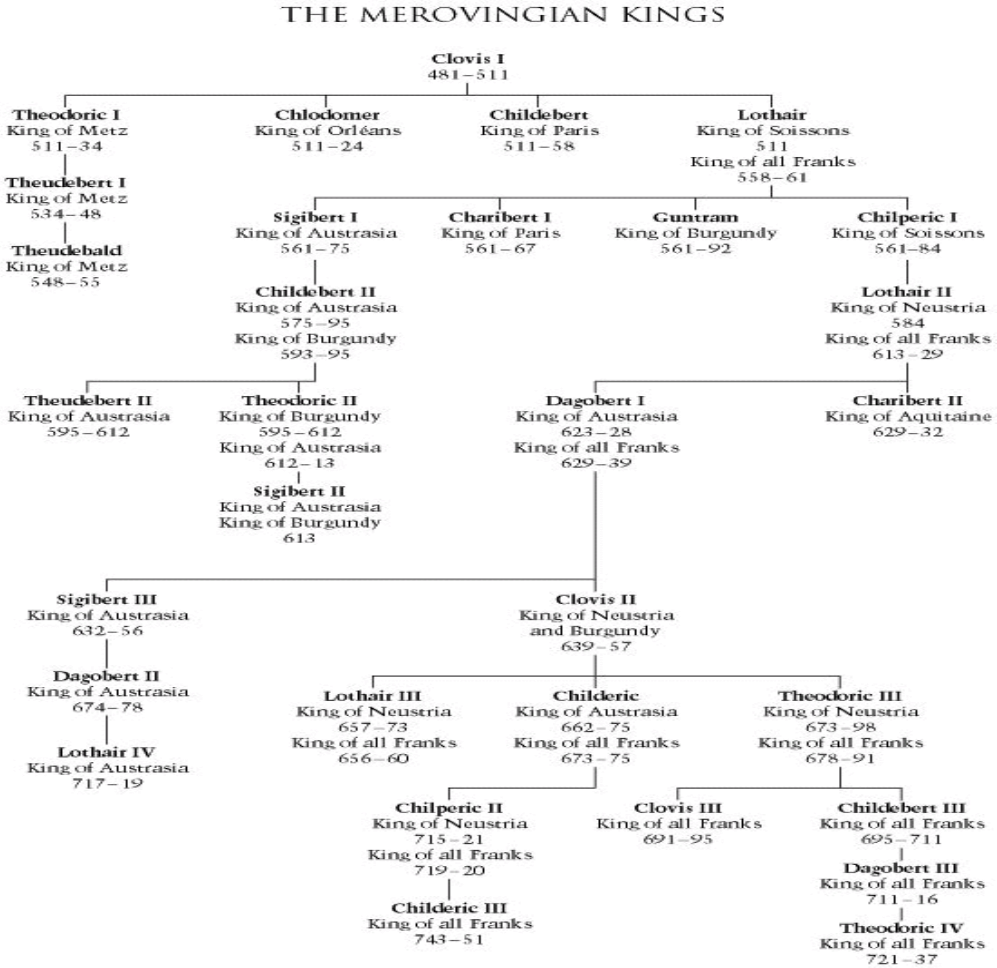
security



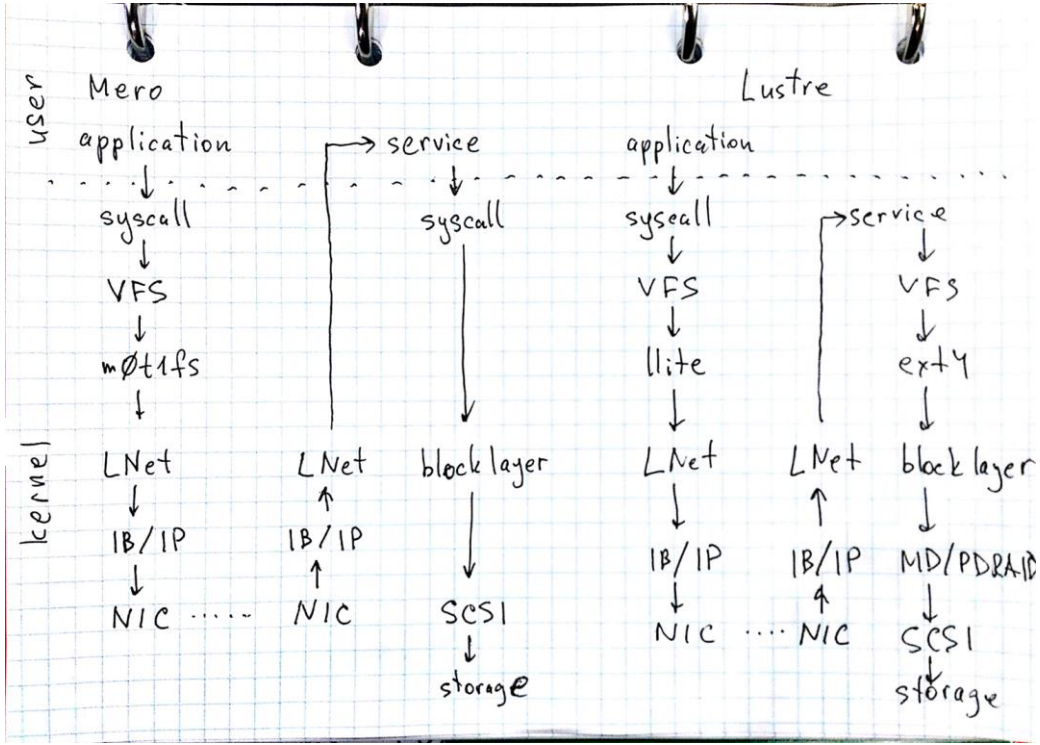
questions?



use cases

- IO data-flow end-to-end
- lookup path through all layers
- LOMO/WOMO: server and client failure

data-flow



lookup: m0t1fs

```
$ ls -l foo
```

- stat("foo", &stbuf);
  - m0t1fs_lookup(dir, dentry, nd)
    - fop = m0_fop_alloc(&m0_fop_lookup_fopt);
    - m0_rpc_post(fop)
    - m0_rpc_item_wait_for_reply(fop)
    - m0t1fs_iget()

lookup: rpc out

- m0_rpc_post(fop)
  - m0_rpc_item_send()
    - m0_rpc_item_start_timer()
    - m0_rpc_frm_enq_item()
      - frm_insert()
        - **queue add [URGENT, BOUND]**
      - frm_balance()
        - **if (ready) frm_fill_packet()**
          - m0_rpc_packet_add_item()
        - **frm_packet_ready()**
          - m0_net_buffer_add()

lookup: rpc in

- buf_recv_cb() (= [M0_NET_QT_MSG_RECV])
  - net_buf_received()
    - packet_received()
      - item_received()
        - **m0_rpc_slot_reply_received()**
          - item_find(item_xid(reply))
          - req->rio_replied()
          - m0_rpc_item_change_state(req, M0_RPC_ITEM_REPLIED)

- m0_rpc_item_wait_for_reply()

lookup: network out

- m0_net_buffer_add()
  - m0_net_tm_tlink_init_at_tail(buf, ql)
  - nx_ops->xo_buf_add(buf) (= nlx_xo_buf_add)
    - M0_NET_QT_MSG_SEND
    - nlx_core_buf_msg_send()
      - nlx_ucore_ioctl(M0_LNET_BUF_MSG_SEND)

lookup: network in

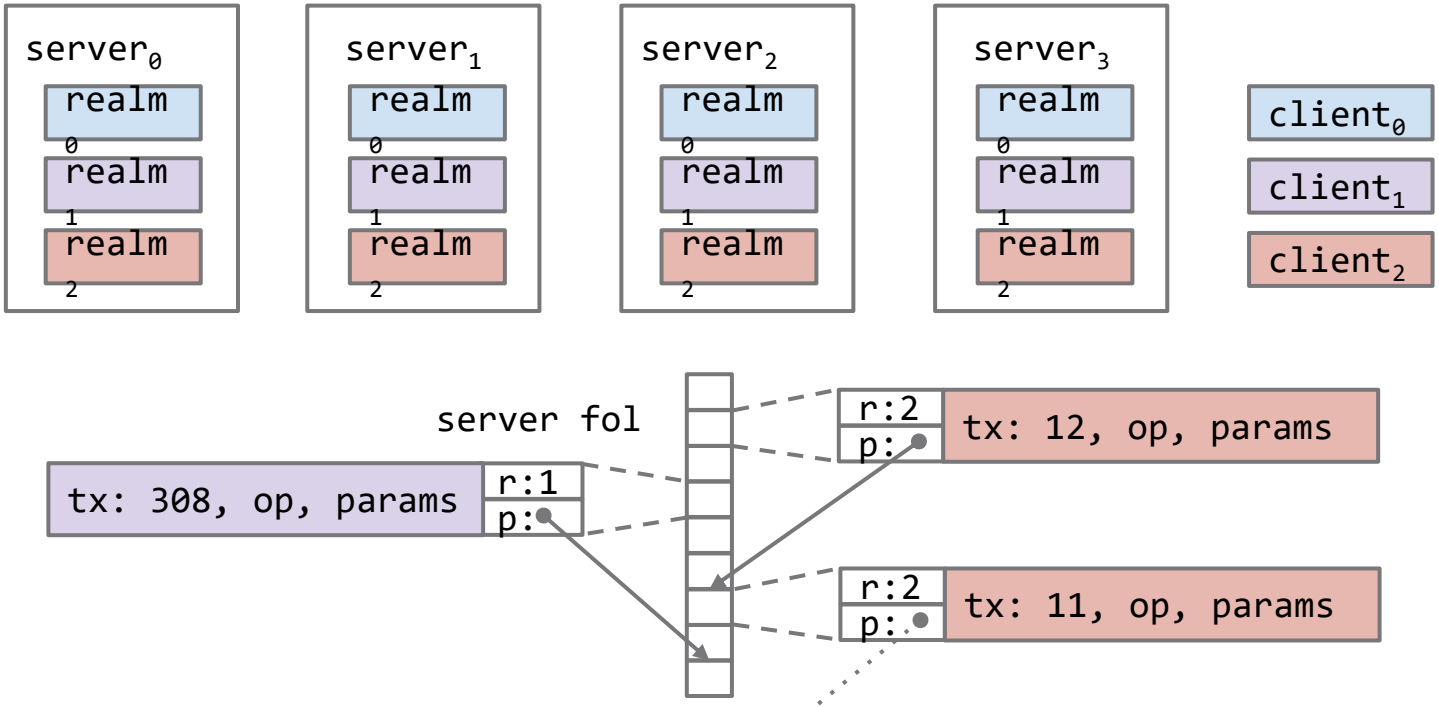
- nlx_tm_ev_worker()
  - !queue.empty() or semaphore_down()
  - queue get
  - m0_net_tm_event_post()
    - buf_recv_cb() (= [M0_NET_QT_MSG_RECV])

lookup: service side

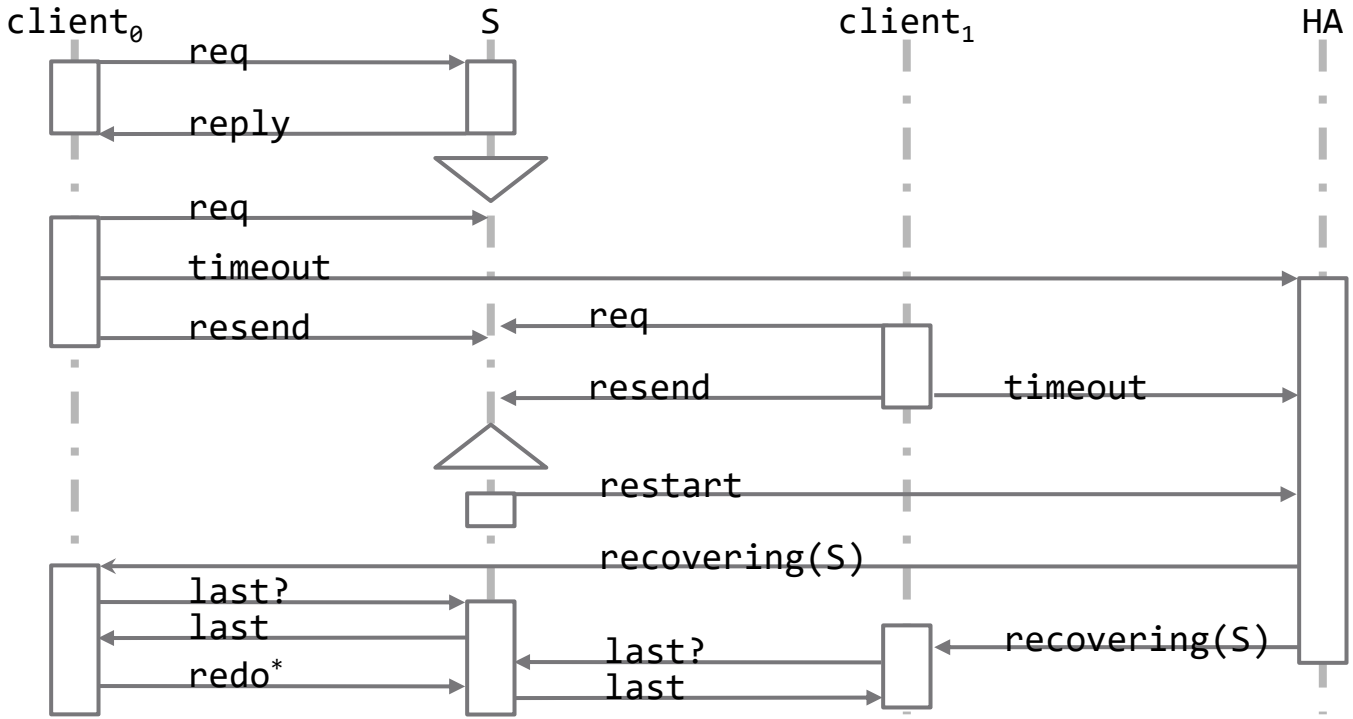
- m0_rpc_item_dispatch()
  - m0_reqh_fop_handle()
    - fop->fto_create(fop, &fom)
    - m0_fom_queue(fom)

- loc_handler_thread()
  - fom_exec(fom)
    - fom->fo_ops->fo_tick(fom)
      - m0_md_tick_getattr()
        - **m0_fom_tick_generic()**
        - **m0_cob_locate()**
          - m0_be_btree_lookup()

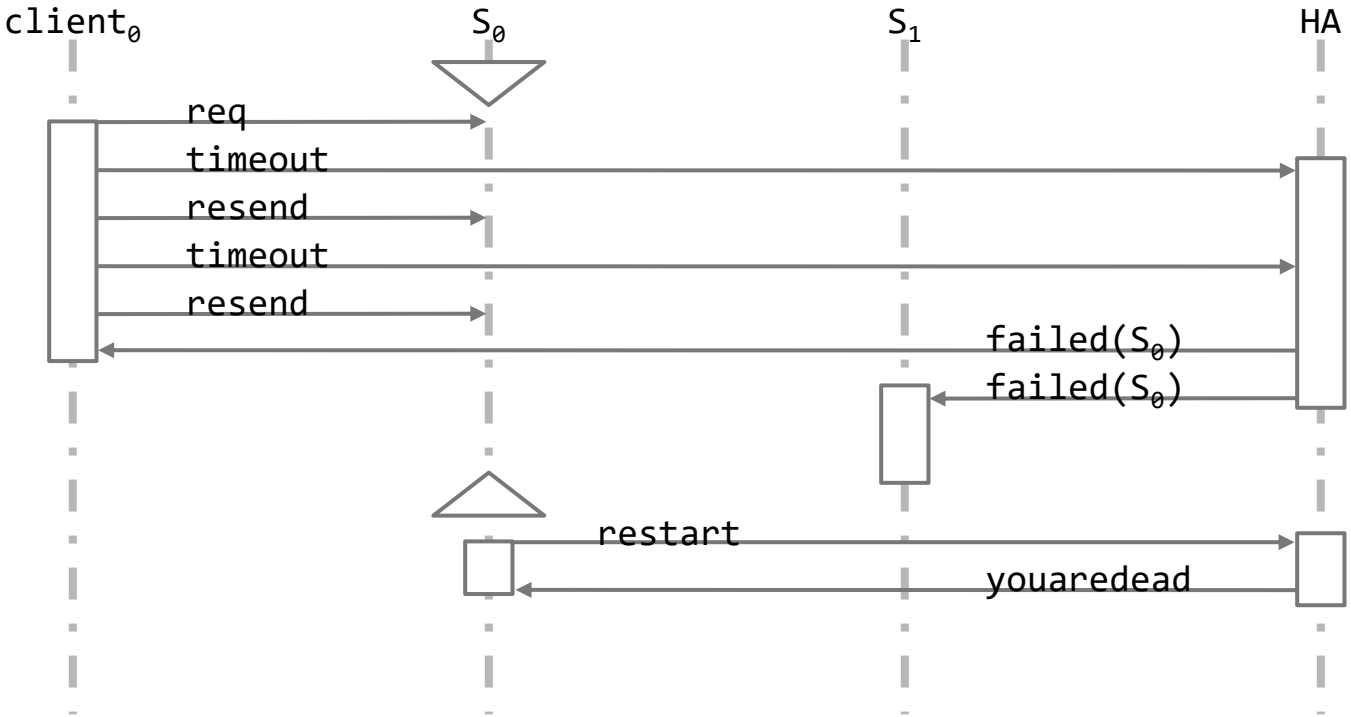
LOMO/WOMO realms



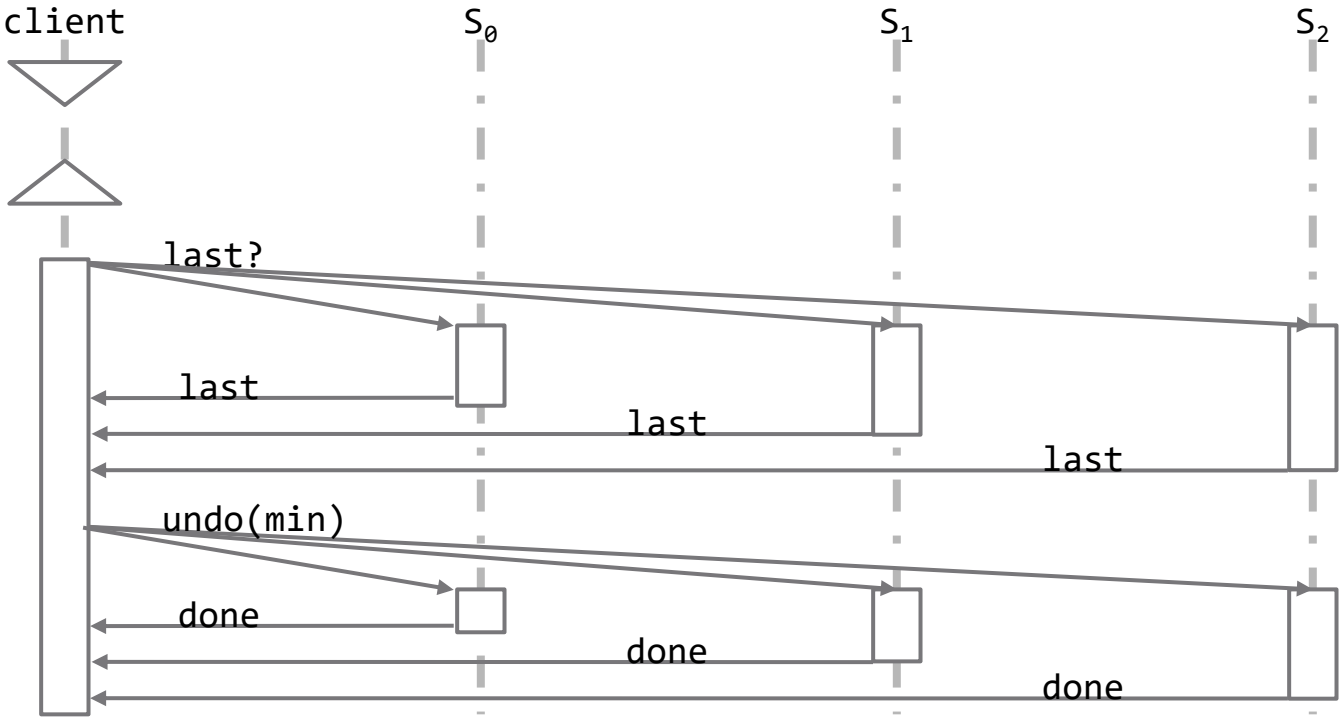
transient server failure



permanent server failure



client failure



io: