Reducing copies in a Lustre-like language with arrays

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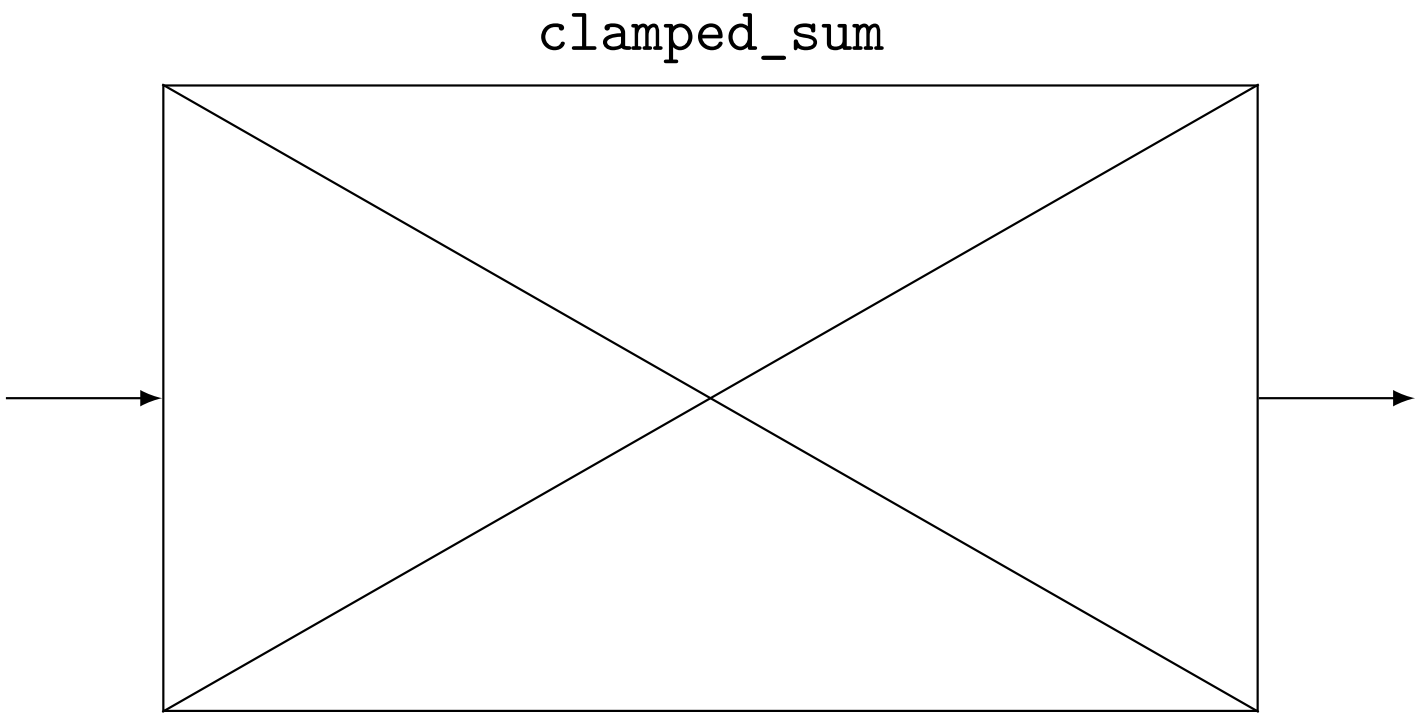
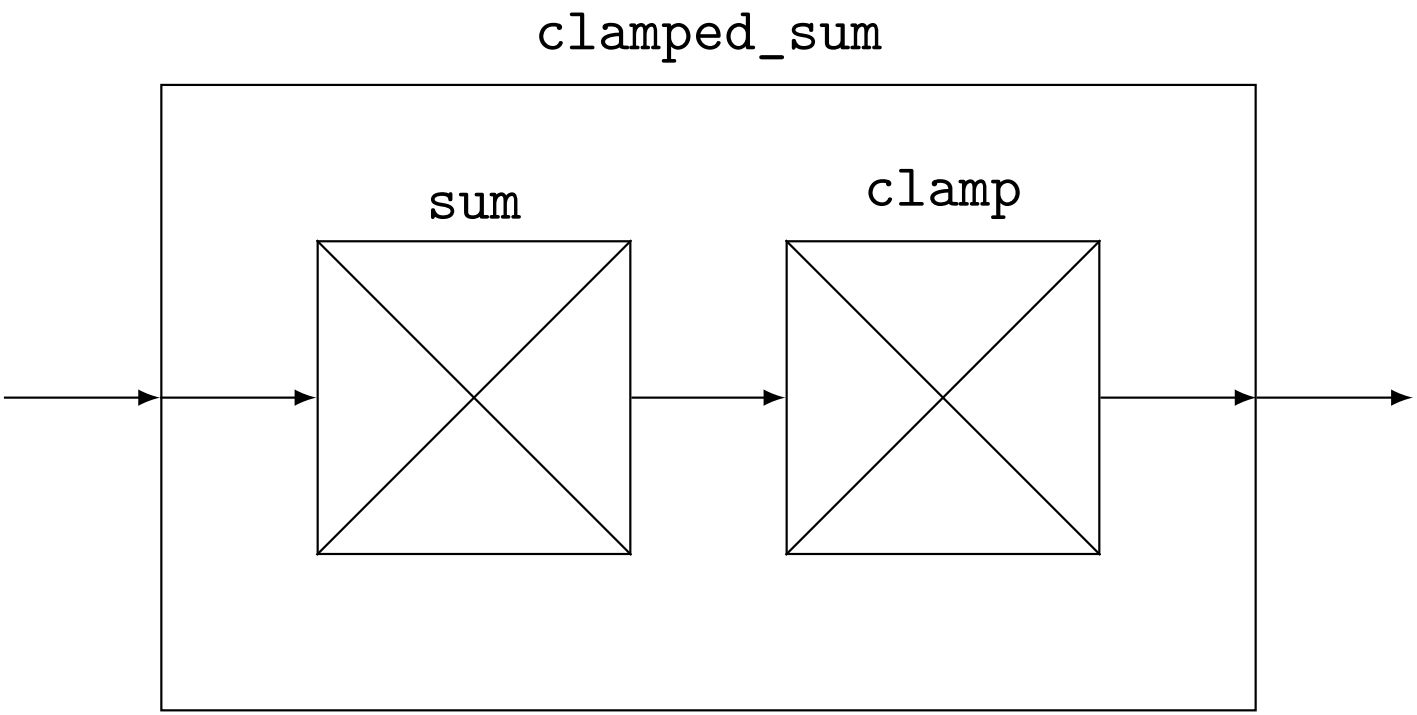
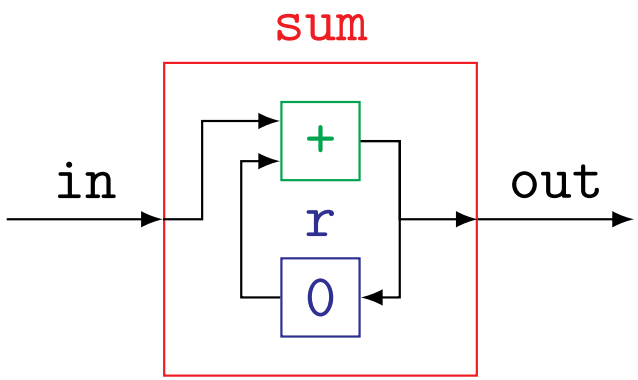
Lustre



Lustre



Lustre



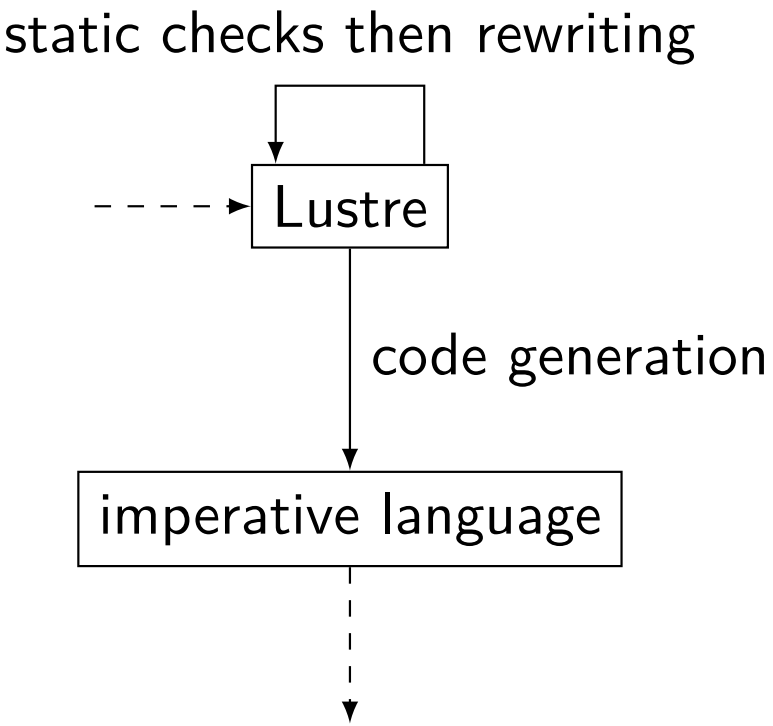

```
node sum(in: int) = (out: int)
  out = in + last r
  r init 0 = out
```

$$\forall n \in \mathbb{N}, out_n = \sum_{i=0}^{n} in_i$$

$$\forall n \in \mathbb{N}, out_n = in_n + r_{n-1}$$

$$r_{-1} = 0 \wedge \forall n \in \mathbb{N}, r_n = out_n$$

Compilation scheme



Constraints on code production

- worst case execution time for required responsiveness
- worst case memory consumption for hardware limitations

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Ownership

```
fn f(a: T);

fn g(x: T) {
  let y = x;
  f(y);
}
```

Ownership

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  let y = x;
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```

Ownership

```
fn f(a: T);

fn g(x: T) {
  f(x);
  f(x);
}
```

Borrowing

```
fn f(a: &mut T, b: &T, c: &T);

fn g(x: T, y: &mut T, z: &T) {
  f(&mut x, ..., ...);
}
```

Borrowing

```
fn f(a: &mut T, b: &T, c: &T);

fn g(x: T, y: &mut T, z: &T) {
  f(&mut *y, ..., ...);
}
```

Borrowing

```
fn f(a: &mut T, b: &T, c: &T);

fn g(x: T, y: &mut T, z: &T) {
  f(&mut *z, ..., ...);
}
```

Borrowing

```
fn f(a: &mut T, b: &T, c: &T);

fn g(x: T, y: &mut T, z: &T) {
  f(..., &x, ...);
}
```

Borrowing

```
fn f(a: &mut T, b: &T, c: &T);

fn g(x: T, y: &mut T, z: &T) {
  f(..., &*y, ...);
}
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Borrowing

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fn f(a: &mut T, b: &T, c: &T);

fn g(x: T, y: &mut T, z: &T) {
  f(..., &*z, ...);
}
```

Borrowing

```
fn f(a: &mut T, b: &T, c: &T);

fn g(x: T, y: &mut T, z: &T) {
  f(&mut x, &x, ...);
}
```

Borrowing

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fn f(a: &mut T, b: &T, c: &T);

fn g(x: T, y: &mut T, z: &T) {
  f(&mut *y, &*y, ...);
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```

Borrowing

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fn f(a: &mut T, b: &T, c: &T);

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Borrowing

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fn f(a: &mut T, b: &T, c: &T);

fn g(x: T, y: &mut T, z: &T) {
  f(&mut x, &*y, &*y);
}
```

Borrowing

```
fn f(a: &mut T, b: &T, c: &T);

fn g(x: T, y: &mut T, z: &T) {
  f(&mut *y, &x, &x);
}
```

Safe Rust and Unsafe Rust

- Safe Rust statically ensures the absence of Undefined Behaviors but can't:
  - dereference raw pointers
  - call `unsafe` functions
  - access fields of `unions`
  - and more...
- Unsafe Rust can, but at the cost of fewer guarantees

Parametric polymorphism and monomorphization

```
fn choose<T>(b: bool, if_true: T, if_false: T)
  -> T {
  if !b { if_false } else { if_true }
}

... choose(b, 1, 2) ...
```

Parametric polymorphism and monomorphization

```
fn choose<T>(b: bool, if_true: T, if_false: T)
  -> T {
  if !b { if_false } else { if_true }
}

... choose::<int>(b, 1, 2) ...
```

Parametric polymorphism and monomorphization

```
fn choose<T>(b: bool, if_true: T, if_false: T)
  -> T {
  if !b { if_false } else { if_true }
}

fn choose_int(b: bool, if_true: int, if_false: int)
  -> int {
  if !b { if_false } else { if_true }
}

... choose_int(b, 1, 2) ...
```

Traits

```
trait Not {
  type Output;
  fn not(self) -> Self::Output;
}

impl Not for &bool {
  type Output = bool;

  fn not(self) -> Self::Output {
    ! *self
  }
}
```

Trait polymorphism

```
fn choose<B: Not<Output = bool>, T>
  (b: B, if_true: T, if_false: T)
  -> T {
  if b.not() { if_false } else { if_true }
}
```

Trait polymorphism

```
fn choose<B: Not<Output = bool>, T>
  (b: B, if_true: T, if_false: T)
  -> T {
  if <B as Not>::not(b) { if_false } else { if_true }
}
```

Trait polymorphism

```
fn choose<T>
   (b: impl Not<Output = bool>, if_true: T, if_false: T)
   -> T {
   if b.not() { if_false } else { if_true }
}
```

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Problem: copies introduced during scheduling

```
node fby_42(x: int) = (y: int)
  i init 0 = ((last i) + 1) % 42
  buf init 0^42 = (last buf)[i] <- x
  y = (last buf)[i]
```

Problem: copies introduced during scheduling

```
node fby_42(x: int) = (y: int)
  i init 0 = ((last i) + 1) % 42
  buf init 0^42 = (last buf)[i] <- x
  y = (last buf)[i]

struct fby_42_state {
  int i;
  int buf[42];
}
```

Problem: copies introduced during scheduling

```
node fby_42(x: int) = (y: int)
  i init 0 = ((last i) + 1) % 42
  buf init 0^42 = (last buf)[i] <- x
  y = (last buf)[i]

void fby_42_reset(struct fby_42_state *self) {
  self->i = 0;
  for (int i = 0; i < 42; i++) {
    self->buf[i] = 0;
  }
}
```

Problem: copies introduced during scheduling

```
node fby_42(x: int) = (y: int)
  i init 0 = ((last i) + 1) % 42
  buf init 0^42 = (last buf)[i] <- x
  y = (last buf)[i]

int fby_42_step(struct fby_42_state *self, int x) {
  int buf_tmp[42]; int y;
  self->i = (self->i + 1) % 42;
  memcpy(self->buf, buf_tmp, 42 * sizeof(int));
  buf_tmp[self->i] = x;
  y = self->buf[self->i];
  memcpy(buf_tmp, self->buf, 42 * sizeof(int));
  return y;
}
```

Problem: copies introduced during scheduling

```
node fby_42(x: int) = (y: int)
  i init 0 = ((last i) + 1) % 42
  y = (last buf)[i]
  buf init 0^42 = (last buf)[i] <- x

int fby_42_step(struct fby_42_state *self, int x) {
  int y;
  self->i = (self->i + 1) % 42;
  y = self->buf[self->i];
  self->buf[self->i] = x;
  return y;
}
```

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Philosophy

- idea: as early as possible, in the synchronous language, we want to talk about expression addresses in the produced imperative code, to take them into account during scheduling
- language primitives should be as copy-free as possible, making most copies explicit
- we design a highly annotated synchronous language, which would be an intermediate language in a full project
- erase locations to get semantics, erase values to get imperative code

```
struct State { ... }
impl State {
  fn reset(&mut self) { ... }
  fn step(&mut self, ...) -> ... { ... }
}
```

Tensors

```
trait Tensor {
  type Repr;
  type Idx;
  type Scal;
  fn get(ptr: NonNull<Self::Repr>, idx: Self::Idx)
    -> NonNull<Self::Scal>;
}
```

Tensors

```
impl<T> Tensor for Atom<T> {
  type Repr = T;
  type Idx = ();
  type Scal = T;

  fn get(ptr: NonNull<Self::Repr>, idx: Self::Idx)
    -> NonNull<Self::Scal> {
    ptr
  }
}
```

Tensors

```
impl<T: Tensor, const N: usize> Tensor for Array<T, N> {
  type Repr = [T::Repr; N];
  type Idx = (usize, T::Idx);
  type Scal = T::Scal;

  fn get(ptr: NonNull<Self::Repr>, idx: Self::Idx)
    -> NonNull<Self::Scal> {
    T::get(ptr.cast::<T::Repr>().add(idx.0), idx.1)
  }
}
```

Views

```
trait View: Copy {
  type Tensor: Tensor;
  fn get(self, idx: <Self::Tensor as Tensor>::Idx)
    -> NonNull<<Self::Tensor as Tensor>::Scal>;
}
```

Views

```
struct Pointer<T: Tensor>(NonNull<T::Repr>);

impl<T: Tensor> View for Pointer<T> {
  type Tensor = T;

  fn get(self, idx: <Self::Tensor as Tensor>::Idx)
    -> NonNull<<Self::Tensor as Tensor>::Scal> {
    T::get(self.0, idx)
  }
}
```

Views

```
struct Projection<V: View>(V, usize);

impl<T: Tensor, const N: usize,
     V: View<Tensor = Array<T, N>>>
  View for Projection<V> {
  type Tensor = T;

  fn get(self, idx: <Self::Tensor as Tensor>::Idx)
    -> NonNull<<Self::Tensor as Tensor>::Scal> {
    self.0.get((self.1, idx))
  }
}

Projection(v, i) = v[i < N]
```

Views

```
struct CutLeft<V: View, const L: usize>(V);

impl<T: Tensor, const N: usize,
     V: View<Tensor = Array<T, N>>, const L: usize>
  View for CutLeft<V, L> {
  type Tensor = Array<T, L>;

  fn get(self, idx: <Self::Tensor as Tensor>::Idx)
    -> NonNull<<Self::Tensor as Tensor>::Scal> {
    self.0.get(idx)
  }
}
```

(with $\mathtt{L} < \mathtt{N}$)

$\mathtt{CutLeft::<\_, L>(v)} = \lambda i < \mathtt{L}.\ \mathtt{v}[i < \mathtt{N}]$

Views

```
struct CutRight
  <V: View, const L: usize, const R: usize>(V);

impl<T: Tensor, const N: usize,
     V: View<Tensor = Array<T, N>>,
     const L: usize, const R: usize>
  View for CutLeft<V, L, R> {
  type Tensor = Array<T, R>;

  fn get(self, idx: <Self::Tensor as Tensor>::Idx)
    -> NonNull<<Self::Tensor as Tensor>::Scal> {
    self.0.get((idx.0 + L, idx.1))
  }
}
```

(with $\mathtt{L} + \mathtt{R} = \mathtt{N}$)

$\mathtt{CutRight::<\_, L, R>(v)} = \lambda i < \mathtt{R}.\ \mathtt{v}[i + \mathtt{L} < \mathtt{N}]$

Views

```
struct Repeat<V: View, const N: usize>(V);

impl<V: View, const N: usize> View for Repeat<V, N> {
  type Tensor = Array<V::Tensor, N>;

  fn get(self, idx: <Self::Tensor as Tensor>::Idx)
    -> NonNull<<Self::Tensor as Tensor>::Scal> {
    self.0.get(idx.1)
  }
}
```

`Repeat::<_, N>(v)` $= \lambda i < \mathtt{N}.\ \mathtt{v}$

Views

```
struct Single<V: View>(V);

impl<V: View> View for Single<V> {
  type Tensor = Array<V::Tensor, 1>;

  fn get(self, idx: <Self::Tensor as Tensor>::Idx)
    -> NonNull<<Self::Tensor as Tensor>::Scal> {
    self.0.get(idx.1)
  }
}
```

$\texttt{Single(v)} = \lambda i < 1.\ \texttt{v}$

Views

```
struct Extract<V: View>(V);

impl<T: Tensor, V: View<Tensor = Array<T, 1>>>
  View for Extract<V> {
  type Tensor = T;

  fn get(self, idx: <Self::Tensor as Tensor>::Idx)
    -> NonNull<<Self::Tensor as Tensor>::Scal> {
    self.0.get((0, idx))
  }
}
```

$\texttt{Extract(v)} = \texttt{v}[0 < 1]$

Views

```
struct Reverse<V: View>(V);

impl<T: Tensor, const N: usize,
     V: View<Tensor = Array<T, N>>>
  View for Reverse<V> {
  type Tensor = Array<T, N>;

  fn get(self, idx: <Self::Tensor as Tensor>::Idx)
    -> NonNull<<Self::Tensor as Tensor>::Scal> {
    self.0.get((N - 1 - idx.0, idx.1))
  }
}
```

$\texttt{Reverse(v)} = \lambda i < \texttt{N}.\ \texttt{v}[\texttt{N} - 1 - i < \texttt{N}]$

Views

```
struct Transpose<V: View>(V);

impl<T: Tensor, const N: usize, const M: usize,
     V: View<Tensor = Array<Array<T, M>, N>>>
  View for Transpose<V> {
  type Tensor = Array<Array<T, N>, M>;

  fn get(self, idx: <Self::Tensor as Tensor>::Idx)
    -> NonNull<<Self::Tensor as Tensor>::Scal> {
    self.0.get((idx.1.0, (idx.0, idx.1.1)))
  }
}
```

$\texttt{Transpose(v)} = \lambda i < \texttt{M}.\ \lambda j < \texttt{N}.\ \texttt{v}\,[j < \texttt{N}]\,[i < \texttt{M}]$

Views

```
struct Split<V: View, const L: usize, const C: usize>(V);

impl<T: Tensor, const N: usize,
     V: View<Tensor = Array<T, N>>,
     const L: usize, const C: usize>
  View for Split<V, L, C> {
  type Tensor = Array<Array<T, C>, L>;

  fn get(self, idx: <Self::Tensor as Tensor>::Idx)
    -> NonNull<<Self::Tensor as Tensor>::Scal> {
    self.0.get((idx.0 * C + idx.1.0, idx.1.1))
  }
}
```

(with $\mathtt{L} \times \mathtt{C} = \mathtt{N}$)

$\mathtt{Split::<\_, L, C>(v)} = \lambda i < \mathtt{L}.\ \lambda j < \mathtt{C}.\ \mathtt{v}[i \times \mathtt{C} + j < \mathtt{N}]$

Views

```
struct Window<V: View, const W: usize, const S: usize>(V);

impl<T: Tensor, const N: usize,
     V: View<Tensor = Array<T, N>>,
     const W: usize, const S: usize>
  View for Window<V, W, S> {
  type Tensor = Array<Array<T, W>, S>;

  fn get(self, idx: <Self::Tensor as Tensor>::Idx)
    -> NonNull<<Self::Tensor as Tensor>::Scal> {
    self.0.get((idx.0 + idx.1.0, idx.1.1))
  }
}
```

(with $\mathtt{W} + \mathtt{S} - 1 = \mathtt{N}$)

$\mathtt{Window::<\_, W, S>(v)} = \lambda i < \mathtt{S}.\ \lambda j < \mathtt{W}.\ \mathtt{v}[i + j < \mathtt{N}]$

Views

```
struct Sample<V: View, const S: usize, const SS: usize>(V);

impl<T: Tensor, const N: usize,
     V: View<Tensor = Array<T, N>>,
     const S: usize, const SS: usize>
  View for Sample<V, S, SS> {
  type Tensor = Array<T, SS>;

  fn get(self, idx: <Self::Tensor as Tensor>::Idx)
    -> NonNull<<Self::Tensor as Tensor>::Scal> {
    self.0.get((idx.0 * S, idx.1))
  }
}
```

(with $\mathtt{S} \times (\mathtt{SS} - 1) + 1 = \mathtt{N}$)

$\mathtt{Sample::<\_, S, SS>(v)} = \lambda i < \mathtt{SS}.\ \mathtt{v}[i \times S < \mathtt{N}]$

Calling conventions

```
node(&l_in: int, x @ l_in, ...) = ...

fn step(&mut self,
        l_in: impl View<Tensor = Atom<int>>,
        ...)
  -> ...;
```

Calling conventions

```
node(&l_in: int, &l_out: int, x @ l_in) = (y @ l_out, ...)

fn step(&mut self,
        l_in: impl View<Tensor = Atom<int>>,
        l_out: impl View<Tensor = Atom<int>>)
  -> ...;
```

Calling conventions

```
node(&l_in: int, &l_out: int, x @ l_in) = (y @ l_out)

fn step(&mut self,
        l_in: impl View<Tensor = Atom<int>>,
        l_out: impl View<Tensor = Atom<int>>);
```

Calling conventions

```
node(&l_in: int, x @ l_in) = (&l_out: int, y @ l_out)

fn step(&mut self,
        l_in: impl View<Tensor = Atom<int>>)
  -> impl View<Tensor = Atom<int>>;
```

Calling conventions

```
node(&l_in: int, &mut l_out: int, x @ l_in) = (y @ l_out)

fn step(&mut self,
        l_in: impl View<Tensor = Atom<int>>,
        l_out: impl View<Tensor = Atom<int>>);
```

Calling conventions

```
node(&mut l_in: int, &mut l_out: int, x @ l_in) =
  (y @ l_out)

fn step(&mut self,
        l_in: impl View<Tensor = Atom<int>>,
        l_out: impl View<Tensor = Atom<int>>);
```

Memories

```
memories (fby_0_n init 0: int @ l_mem)

struct State {
  l_mem: MaybeUninit<<Atom<int> as Tensor>::Repr>,
  ...
}

fn reset(&mut self) { self.l_mem.write(0); ... }

fn step(&mut self, ...) {
  let l_mem: Pointer<Atom<int>> =
    Pointer(
      NonNull::new_unchecked(
        self.l_mem.as_mut_ptr()));
  ...
}
```

Stack

```
stack (&mut l_loc: int)

fn step(&mut self, ...) {
  let l_loc: Pointer<Atom<int>> =
    Pointer(
      NonNull::new_unchecked(
        MaybeUninit::uninit().as_mut_ptr()));
  ...
}
```

Variables locales

```
locals (a @ l_in) (b @ l_out) (c @ l_mem) (d @ l_loc)
```

Clocks and views

```
node ex(c: bool, in) = (out)
  tmp = f(in when c)
  out = g(merge(c, tmp, in when not c))
```

c	T	F	T	T	F	...
in	in_0	in_1	in_2	in_3	in_4	...
in when c	in_0		in_2	in_3		...
tmp	tmp_0		tmp_2	tmp_3		...
in when not c		in_1			in_4	...
merge(c, tmp, in when not c)	tmp_0	in_1	tmp_2	tmp_3	in_4	...
out	out_0	out_1	out_2	out_3	out_4	...

Clocks and views

```
node ex(c: bool, in) = (out)
  tmp = f(in when c)
  out = g(merge(c, tmp, in when not c))
```

c	T	F	T	T	F	...
in	in_0	in_1	in_2	in_3	in_4	...
in when c	in_0	?	in_2	in_3	?	...
tmp	tmp_0	?	tmp_2	tmp_3	?	...
in when not c	?	in_1	?	?	in_4	...
merge(c, tmp, in when not c)	tmp_0	in_1	tmp_2	tmp_3	in_4	...
out	out_0	out_1	out_2	out_3	out_4	...

Clocks and views

$$\frac{\texttt{c: } C_1 \texttt{ + } \cdots \texttt{ + } C_n \qquad \texttt{x @ l}}{\texttt{x when c = } C_i \texttt{ @ l on c = } C_i}$$

$$\frac{\texttt{c: } C_1 \texttt{ + } \cdots \texttt{ + } C_n \qquad \forall i,\ \texttt{e}_i \texttt{ @ l on c = } C_i}{\texttt{merge(c, } C_1 \texttt{ => e}_1\texttt{, } \cdots\texttt{, } C_n \texttt{ => e}_n\texttt{) @ l}}$$

Arrays and views

$$\frac{\texttt{l: [T; M + N]} \qquad \texttt{x @ l}}{\texttt{fst(x as [\_; M] ++ [\_; N]) @ fst(l as [\_; M] ++ [\_; N])}}$$

$$\frac{\texttt{l: [T; M + N]} \qquad \texttt{x @ l}}{\texttt{snd(x as [\_; M] ++ [\_; N]) @ snd(l as [\_; M] ++ [\_; N])}}$$

$$\frac{\begin{array}{l}\texttt{x @ fst(l as [\_; M] ++ [\_; N])} \\ \texttt{y @ snd(l as [\_; M] ++ [\_; N])}\end{array}}{\texttt{x ++ y @ l}}$$

Arrays and views

$$\frac{\texttt{l: [T; N]} \qquad \texttt{x @ l}}{\texttt{x[i] @ l[i]}}$$

Arrays and views

$$\frac{\texttt{l: [T; N]} \qquad \texttt{x @ l}}{\texttt{x[i] @ l[i]}} \qquad\qquad \frac{\texttt{l: [T; N]} \qquad \texttt{x @ l}}{\texttt{x[\textbackslash i] @ l[\textbackslash i]}}$$

$$\frac{\texttt{x @ l[i]} \qquad \texttt{y @ l[\textbackslash i]}}{\texttt{update(y, x) @ l}}$$

$$\texttt{[arr with i <- x]} = \texttt{update(arr[\textbackslash i], x)}$$

Arrays and views

$$\frac{\texttt{x @ l}}{\texttt{[x] * N @ [l] * N}}$$

Interference of views

$$\frac{\mathtt{l}_1 \neq \mathtt{l}_2}{\mathtt{l}_1 \parallel \mathtt{l}_2} \qquad \frac{i \neq j}{\mathtt{v\ on\ c} = \mathtt{C}_i \parallel \mathtt{v\ on\ c} = \mathtt{C}_j}$$

$$\frac{}{\mathtt{fst(v\ as\ [\_;\ M]\ ++\ [\_;\ N])} \parallel \mathtt{snd(v\ as\ [\_;\ M]\ ++\ [\_;\ N])}}$$

$$\frac{}{\mathtt{v[i]} \parallel \mathtt{v[\backslash i]}}$$

$$\frac{\mathtt{v}_1 \parallel \mathtt{v}_2}{\mathtt{v}_2 \parallel \mathtt{v}_1} \qquad \frac{\mathtt{v}_1 \parallel \mathtt{v}_2}{\mathtt{v}_1\ \mathtt{on\ c} = \mathtt{C} \parallel \mathtt{v}_2} \qquad \frac{\mathtt{v}_1 \parallel \mathtt{v}_2}{[\mathtt{v}_1]\ \mathtt{*\ N} \parallel \mathtt{v}_2} \qquad \ldots$$

Node call and reset

```
b = (f on c1 = C1 reset every c2 = C2, c3 = C3)
      (N; idx, e_idx; &l, a, &mut l' on a = true)
```

$\forall s, \forall i_1\ i_2,$
$\forall(\&l_1\text{: bool})(x\ @\ l_1)(\&\text{mut}\ l_2\text{: [int; s] on } x = \text{true}),$
$\exists(y\ @\ l_2[i_1])$

```
struct State {
  instance_f_42: State_f<N>,
  ...
}
if let C1 = l_c1.get(()).read() {
  self.instance_f_42
    .step(idx, l_e_idx.get(()).read() as usize, l, l');
}
```

Node call and reset

```
b = (f on c1 = C1 reset every c2 = C2, c3 = C3)
      (N; idx, e_idx; &l, a, &mut l' on a = true)
```

$\forall s, \forall i_1\ i_2,$

$\forall(\&l_1\text{: bool})(x\ @\ l_1)(\&\text{mut}\ l_2\text{: [int; s] on } x = \text{true}),$

$\exists(y\ @\ l_2[i_1])$

```
struct State {
  instance_f_42: State_f<N>,
  ...
}
if let C2 = l_c2.get(()).read() {
  self.instance_f_42.reset();
}
```

Node call and reset

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Scheduling

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node(&mut l1: int, x @ l1) = (z @ l1)
  stack (&mut l2: bool)
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  c1 = i(&mut l2)
  c2 = h(&mut l2)
  y = (f on c1)(&mut l1 on c1, x when c1)
  z = (g reset every c1)
        (&l2, &mut l1, c2, merge(c1, y, x whenot c1))
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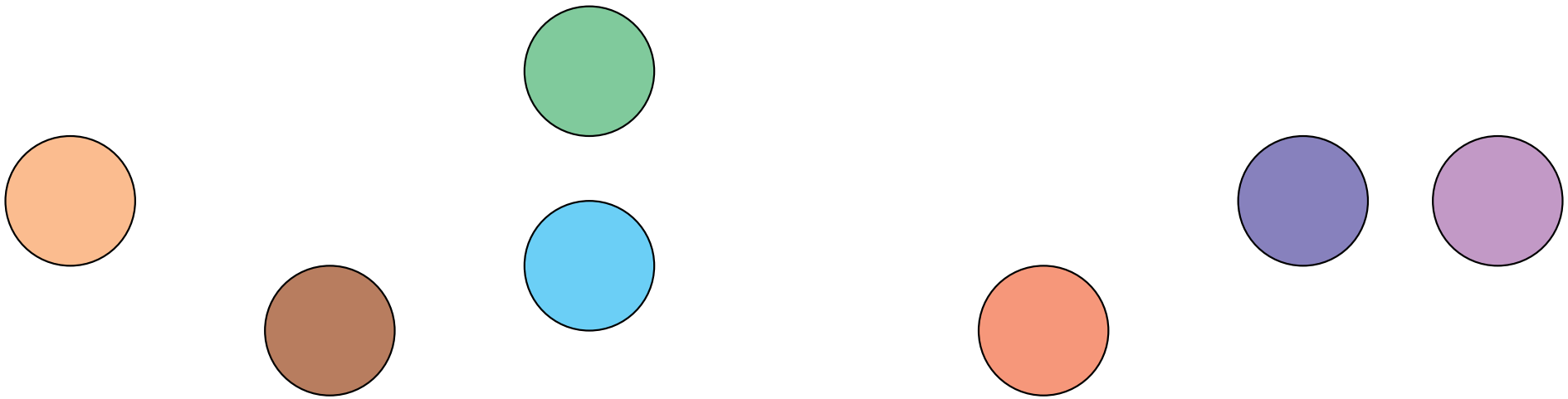

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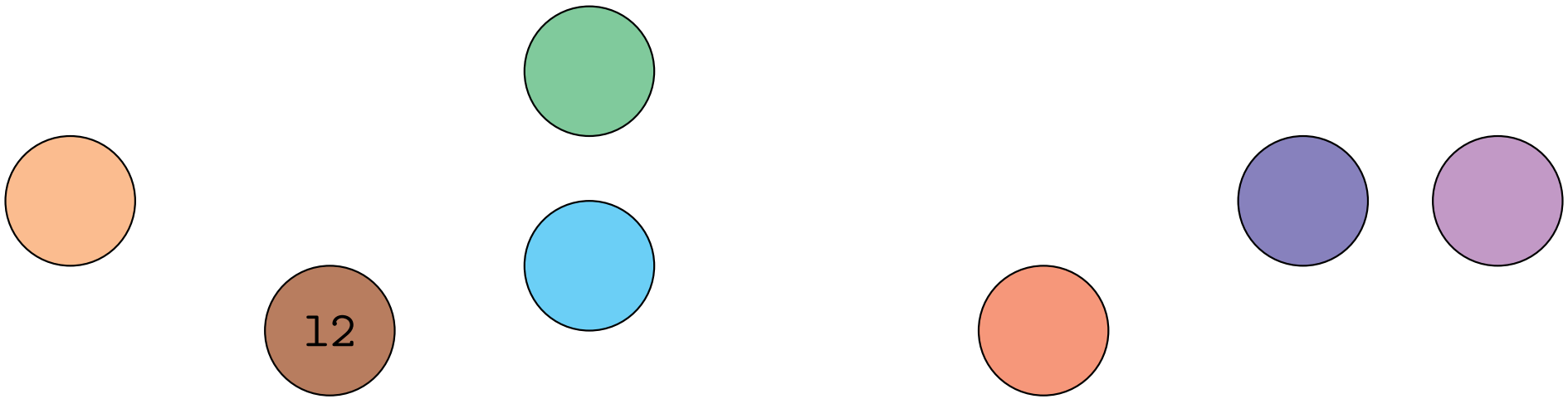

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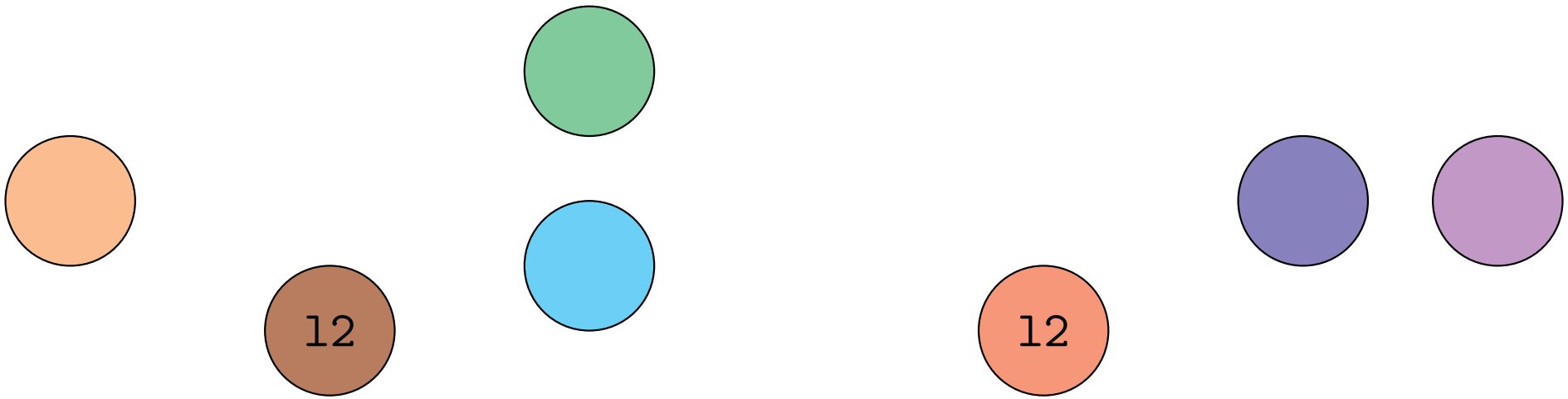

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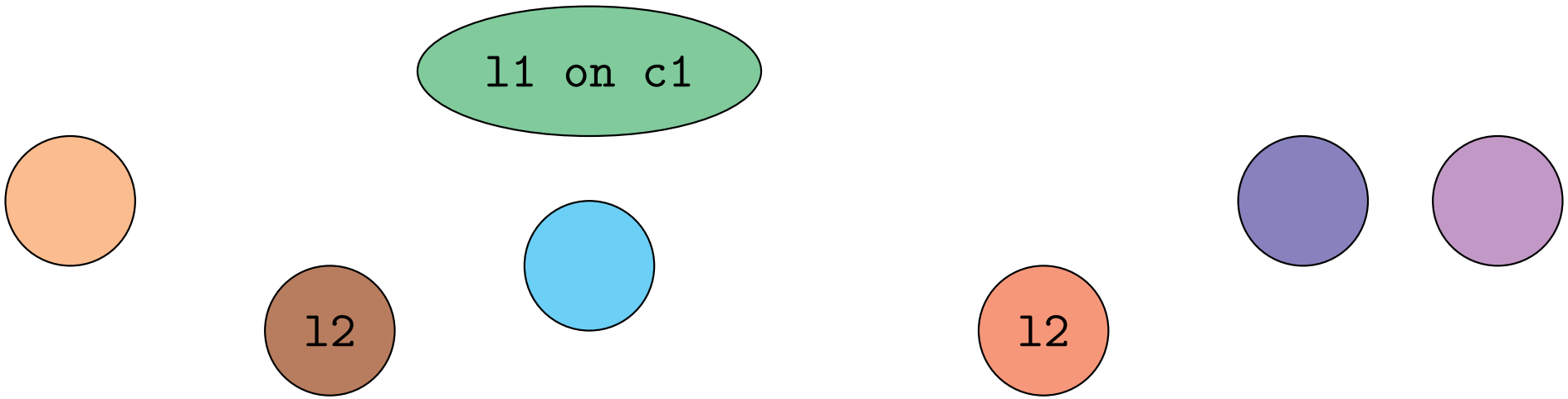

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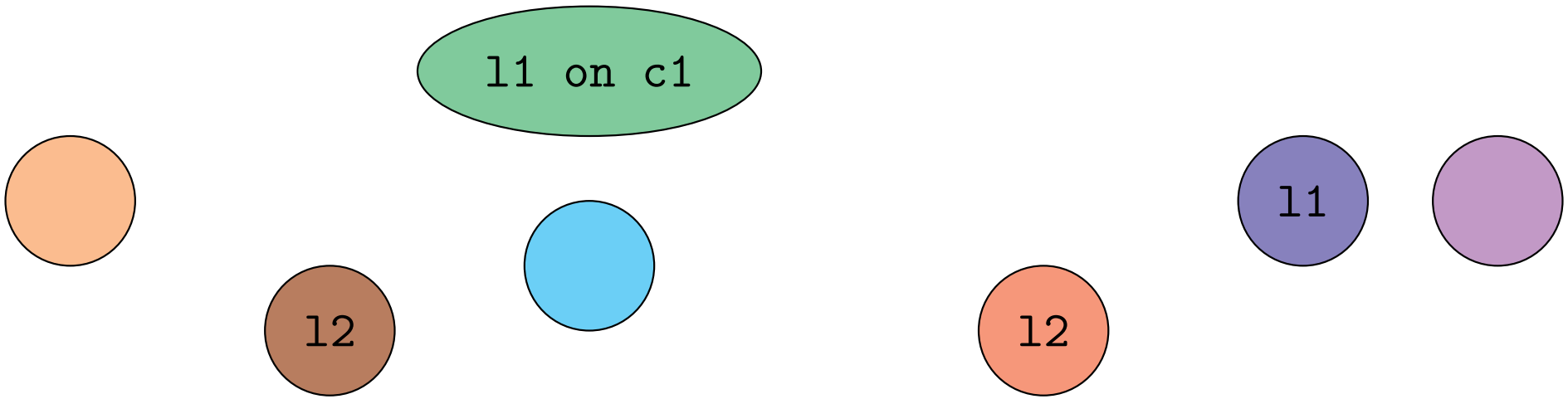

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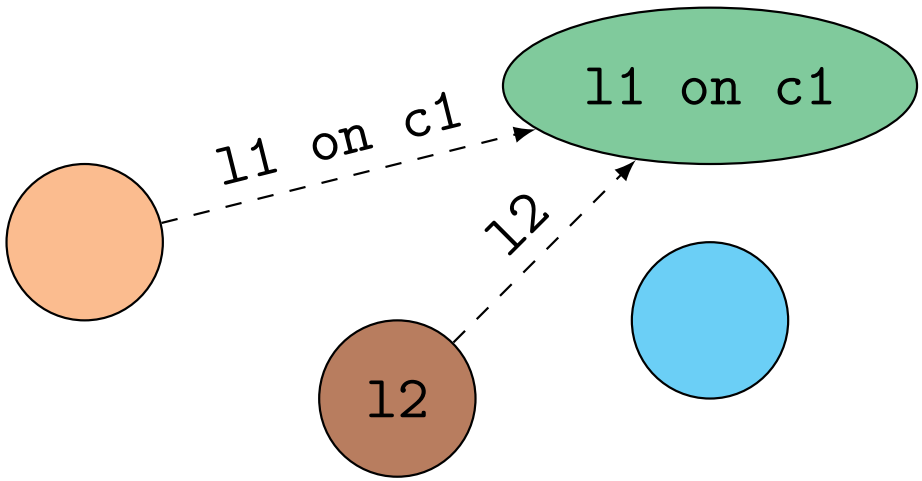

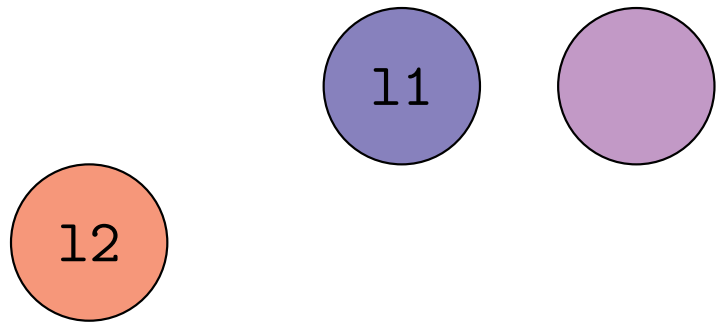

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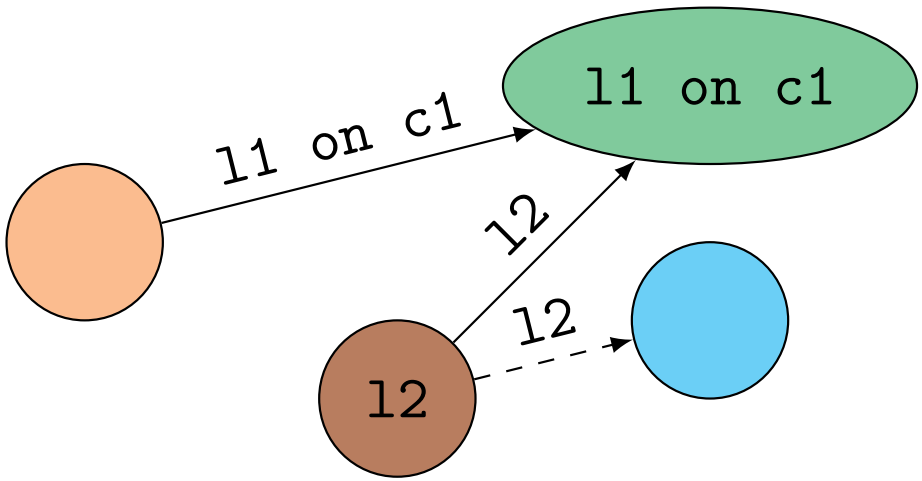

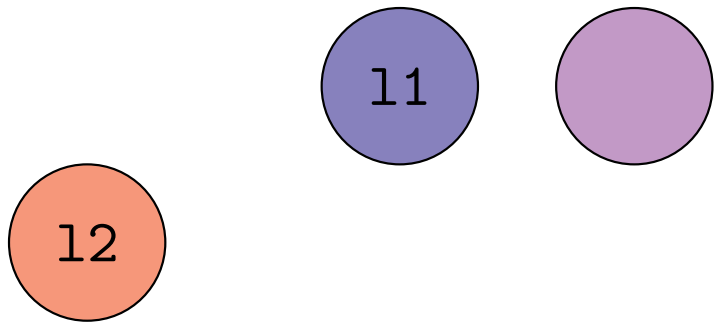

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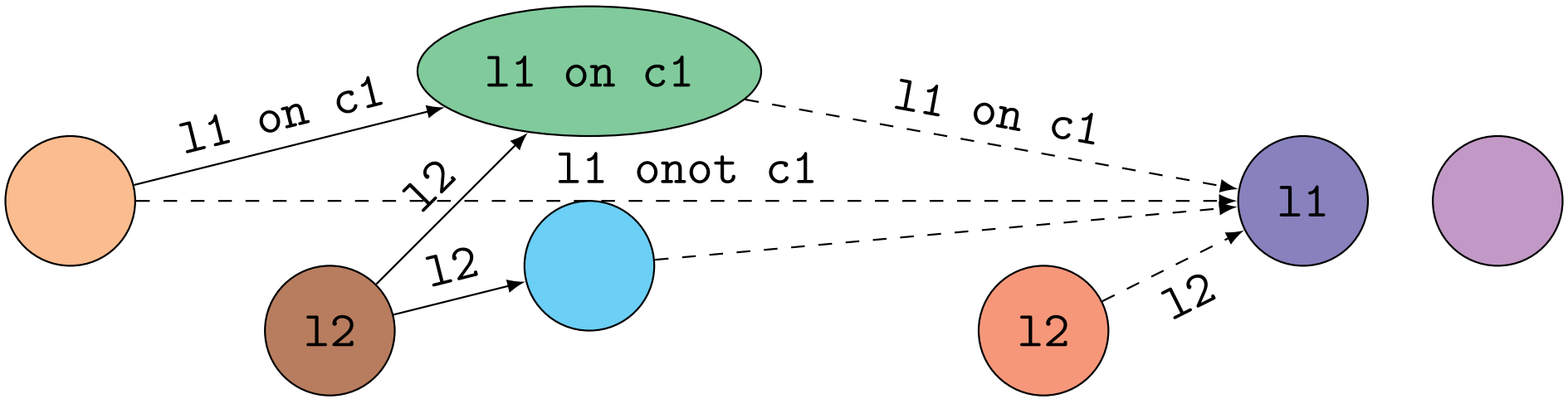

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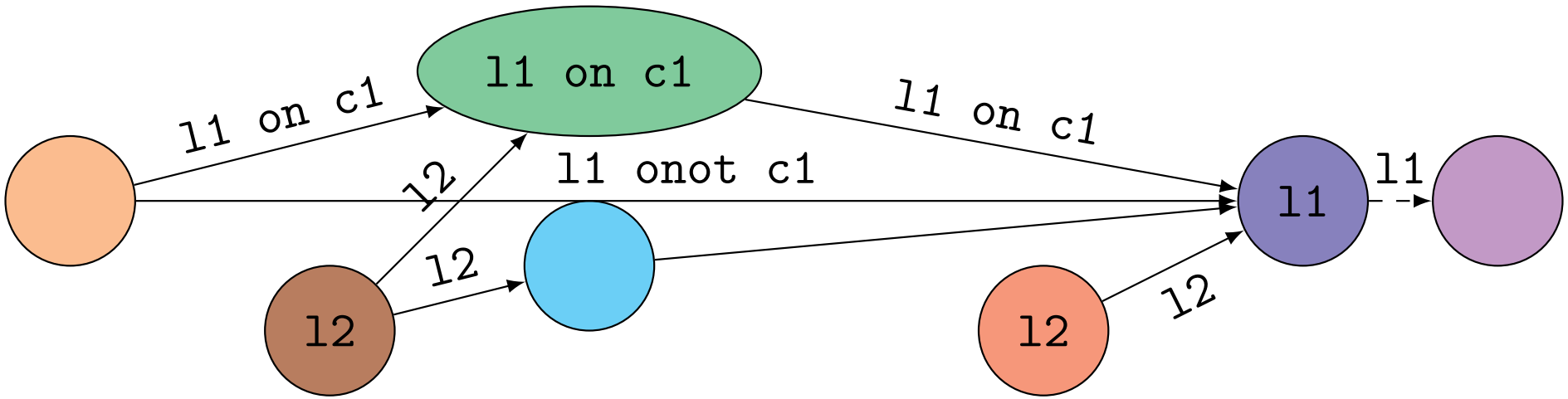

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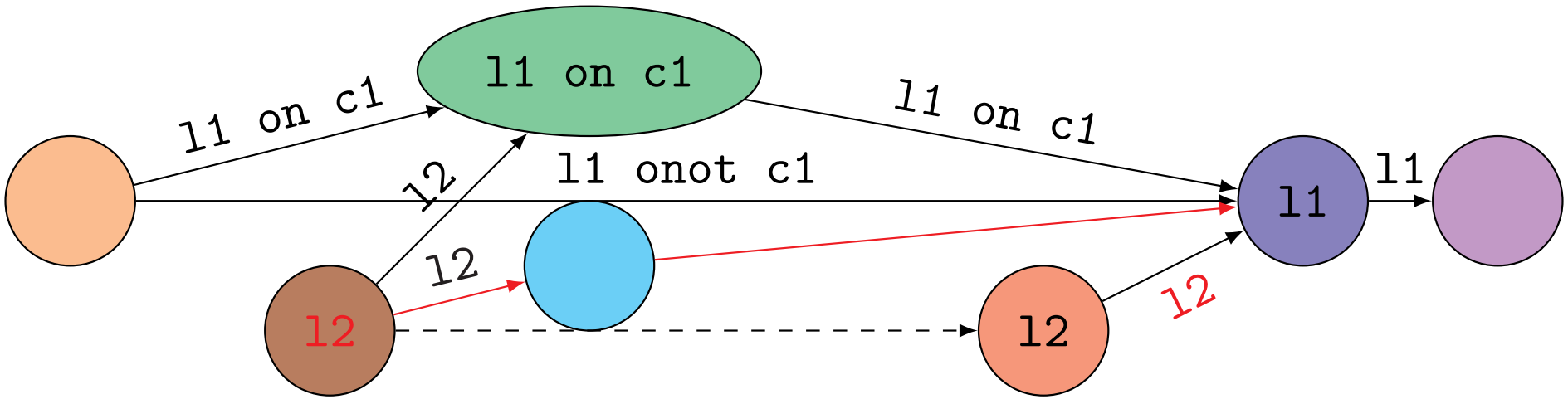

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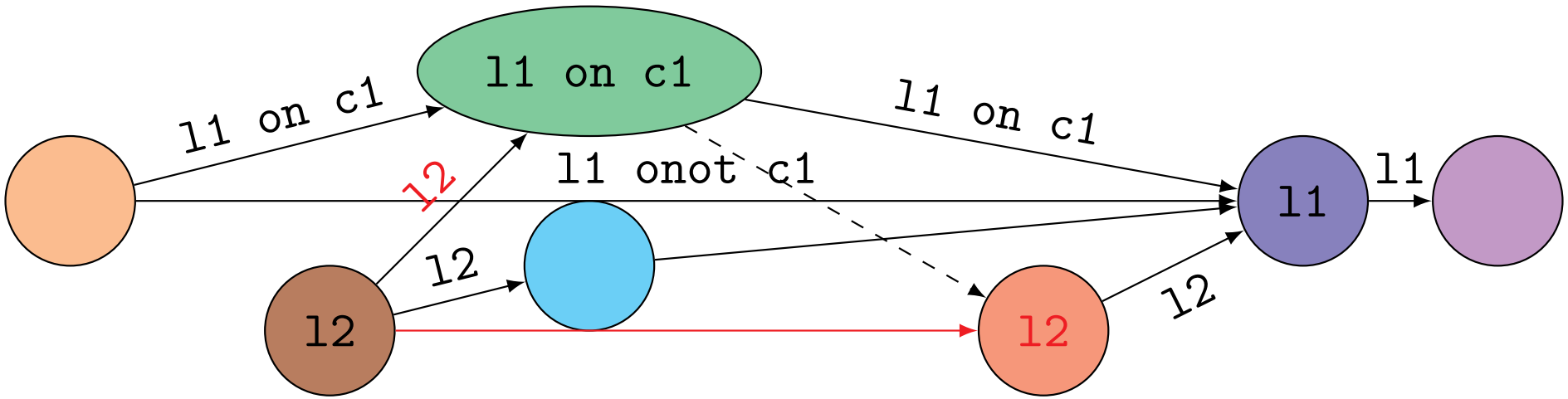

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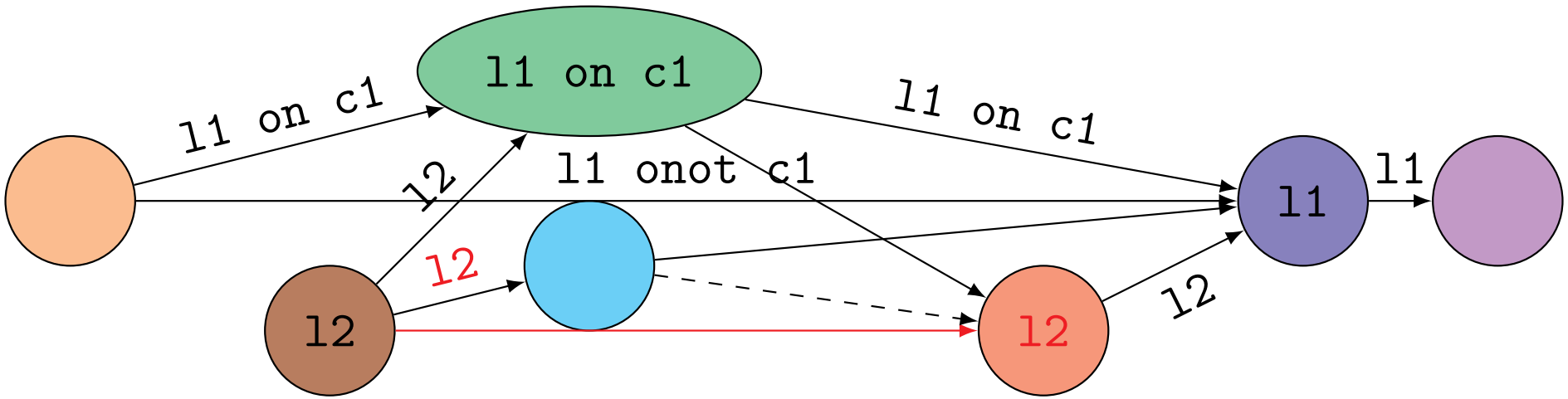

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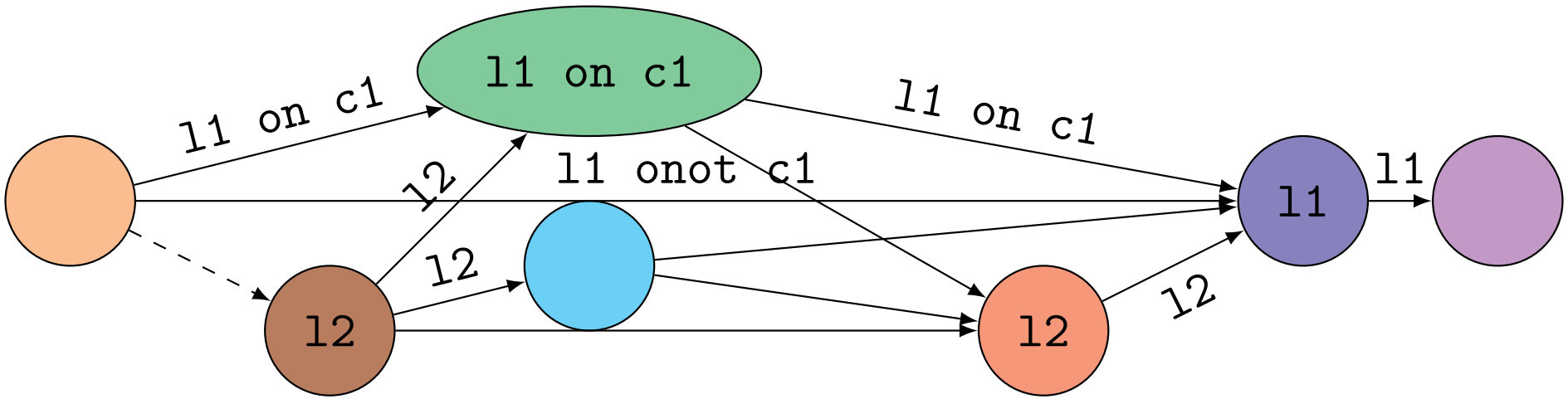

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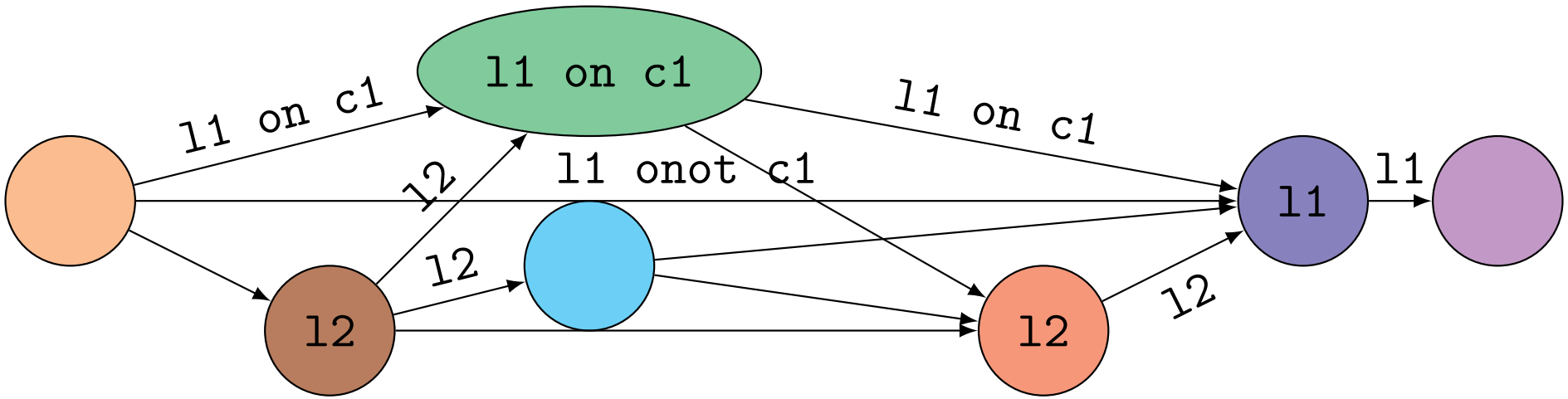

Thank you for your attention!
Any questions?