Stories from a parallel universe

Jana Machutová

Do you feel sudden tension in your brain?

SEMAPHORE

JOIN

JTHREAD

BARRIER

WAIT

DEADLOCKS

FALSE SHARING

ATOMICS

LOCK

CRITICAL SECTION

MEMORY ORDER

MUTEX

DETACH

NOTIFY ALL

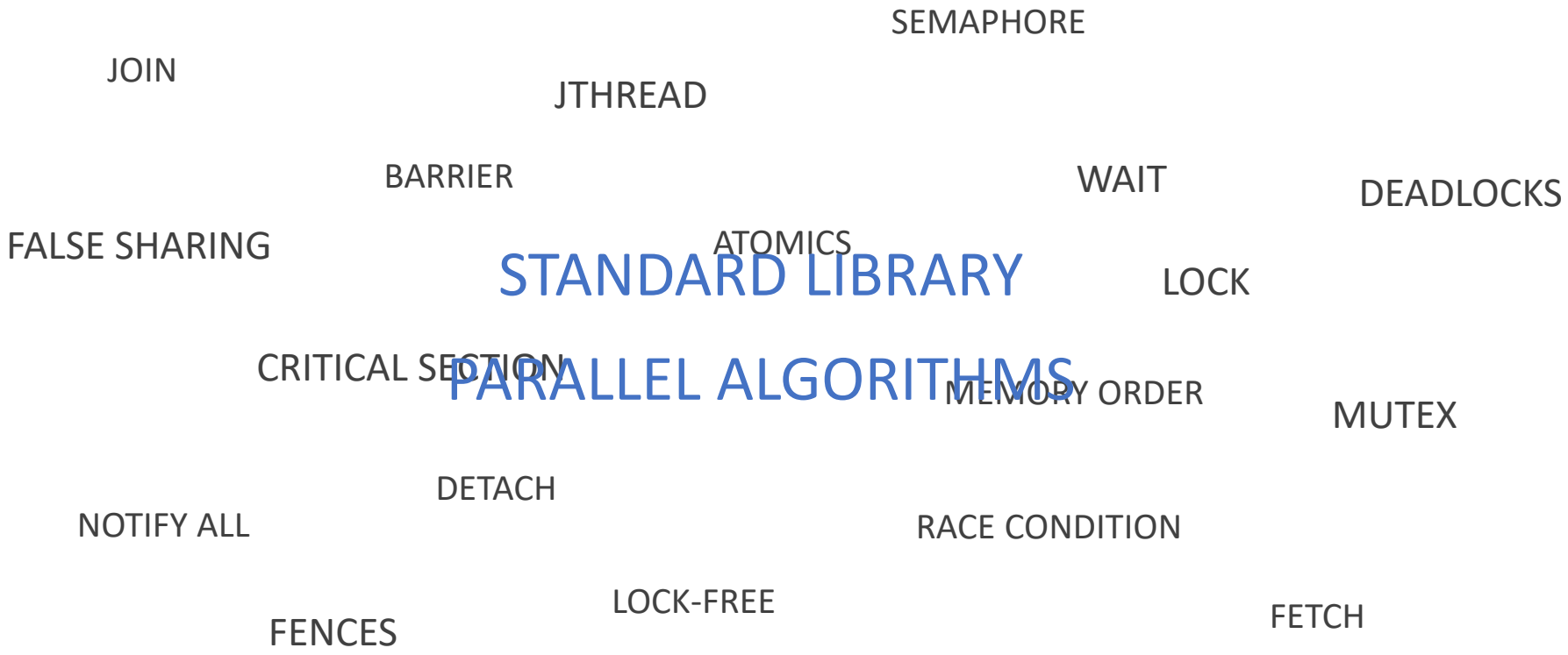
RACE CONDITION

LOCK-FREE

FETCH

FENCES

We have a painkiller for you!



Standard library parallel algorithm

Provides parallel version of most of standard library algorithms

Introduce execution policy parameter

Easy switch between sequential and few types of parallel executions

Well optimized solution to common problems

No need to reinvent parallel wheels

Standard library parallel algorithm

In standard since C++17 with few updates in C++20

Several new algorithms appeared

Several old don’t have any parallel version

Not available for ranges so far

Create new worlds

```
array<animal_species, 1000000> species{...};

vector<jthread> sky_residents;
for_each(species.begin(), species.end(), [&](){
    sky_residents.push_back(jthread([]{
        fly_high();
    }));
});
```

Thread #0 species [0]

Thread #1 species [1]

RESOURCE UNAVAILABLE

Thread #999 999 species [999 999]

```
for_each(execution::par_unseq, species.begin(), species.end(), [](){
    swim_deep();
});
```

Thread #0 species [0 – 9 999]

Thread #1 species [10 000 – 19 999]

Thread #100 species [90 000 – 99 999]

Why do you want to use parallel algorithms

No need for direct manipulation with threads

No need to care about threads lifetime

Easy to switch between sequential and parallel executions

Clever thread management is already part of the package

Why do you want to use parallel algorithms

Widely tested and optimized solution

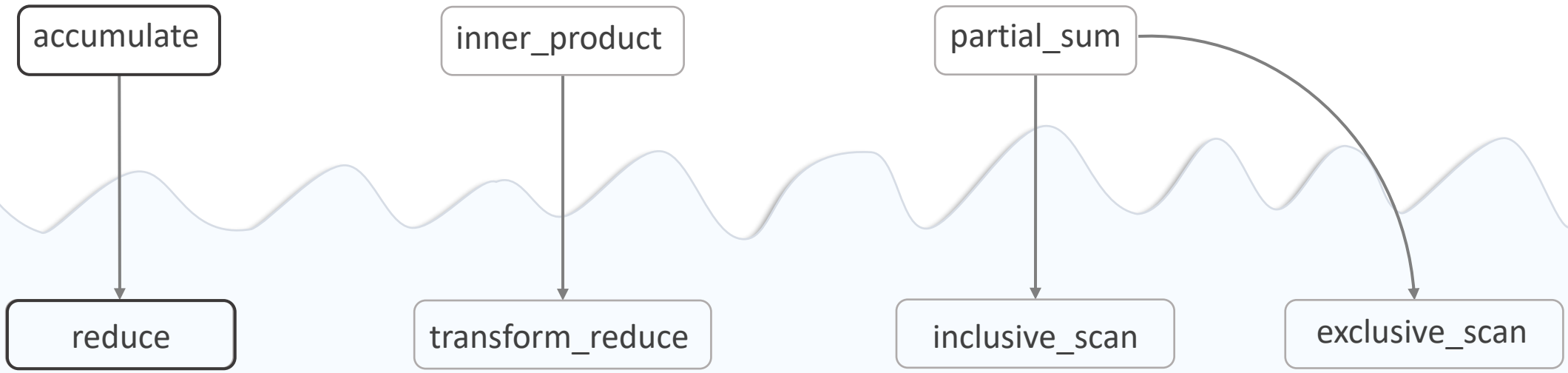
Improved readability

Less error prone

Do not reinvent a wheel – use standard library as much as you can

New algorithms introduced

All of them are here as an alternative to existing sequential only solution



accumulate vs reduce

```
vector<int> counts {68, 15, 4, 45, 18, 3, 2, 11};

accumulate(counts.begin(), counts.end(), 0, plus{});
```

output: **166**

```
reduce(execution::par_unseq, counts.begin(), counts.end(), 0, plus{});
```

output: **166**

accumulate vs reduce

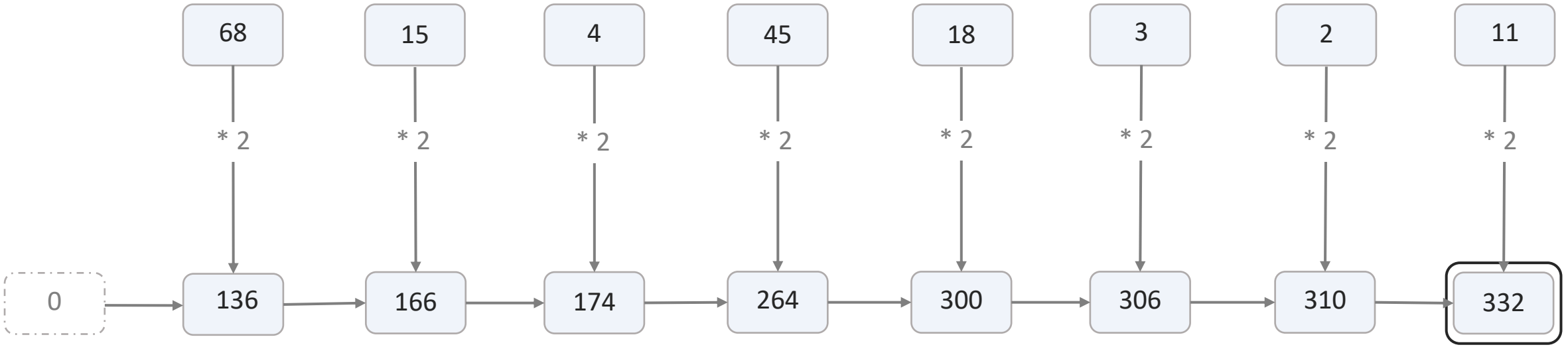
```
vector<int> counts {68, 15, 4, 45, 18, 3, 2, 11};
int         growth_factor = 2;

accumulate(counts.begin(), counts.end(), 0,
    [growth_factor](auto first, auto second){
        return first + second * growth_factor;
});
```

output: **332**

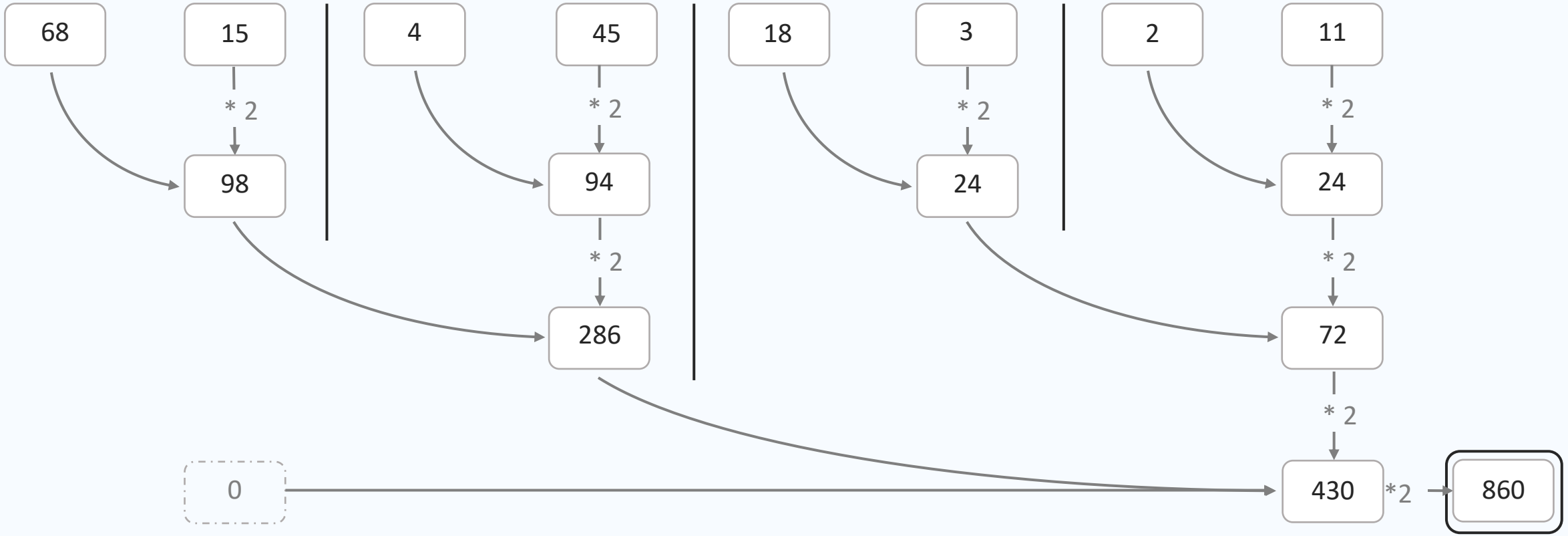
```
reduce(execution::par_unseq, counts.begin(), counts.end(), 0,
    [growth_factor](auto first, auto second){
        return first + second * growth_factor;
});
```

output: **716**

accumulate walktrough



reduce walktrough



0 + 2*(68 + 2*15 + 2*(4 + 2*45) + 2*(18 + 2*3 + 2*(2 + 2* 11))) != 0 + ((((((2*68 + 2*15) + 2*4) + 2*45) + 2*18) + 2*3) + 2*2) + 2* 11

accumulate vs reduce

```
vector<int> counts {68, 15, 4, 45, 18, 3, 2, 11};
int         growth_factor = 2;

accumulate(counts.begin(), counts.end(), 0,
    [growth_factor](const auto first, const auto second){
        return first + second * growth_factor;
});
```

output: **322**

```
reduce(execution::par_unseq, counts.begin(), counts.end(), 0,
    [growth_factor](const auto first, const auto second){
        return first + second * growth_factor;
});
```

output: **716**

accumulate vs reduce - fixed

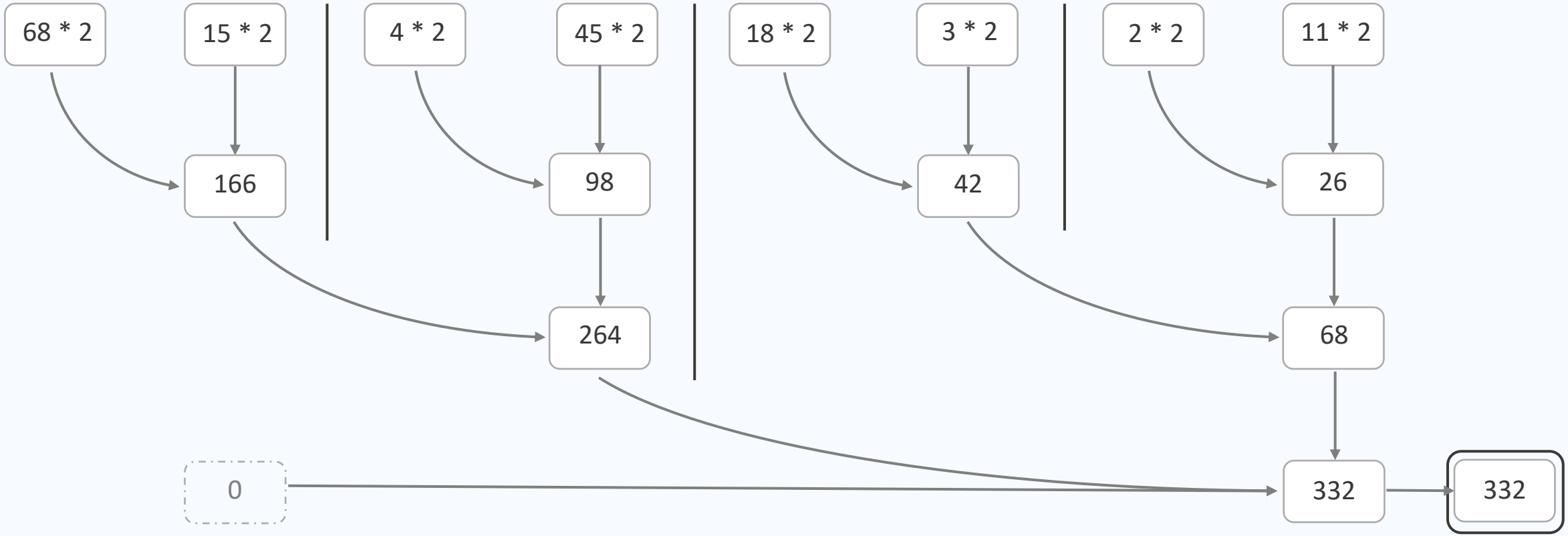
```
vector<int> counts {68, 15, 4, 45, 18, 3, 2, 11};
int         growth_factor = 2;

accumulate(counts.begin(), counts.end(), 0,
    [growth_factor](const auto first, const auto second){
        return first + second * growth_factor;
});
```

output: **332**

```
transform_reduce(execution::par_unseq, counts.begin(), counts.end(), 0, std::plus{},
    [growth_factor](const auto item){
        return item * growth_factor;
});
```

output: **332**

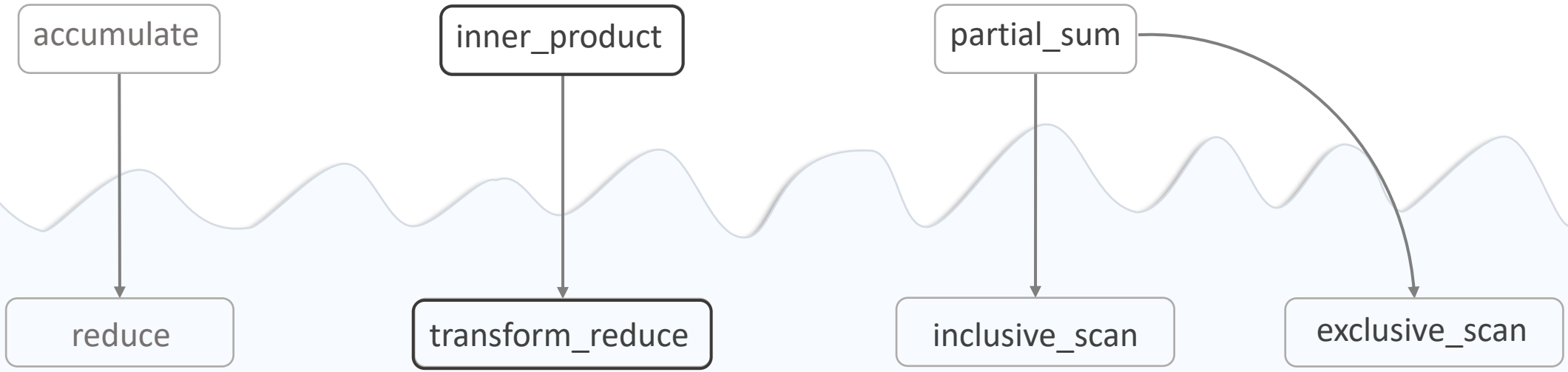
transform_reduce walktrough



0 + (136 + 30 + (8 + 90) + (36 + 6 + (4 + 22))) == 0 + 2*68 + 2*15 + 2*4 + 2*45 + 2*18 + 2*3 + 2*2 + 2* 11

New algorithms introduced

All of them are here as an alternative to existing sequential only solution



inner_product vs transform_reduce

```
vector<int> weights {1, 2, 3, 4, 5, 6, 7, 8};
vector<int> counts {68, 15, 4, 45, 18, 3, 2, 11};

inner_product(counts.begin(), counts.end(), weights.begin(), 0);
```

output: **500**

```
transform_reduce(execution::par_unseq, counts.begin(), counts.end(), weights.begin(), 0);
```

output: **500**

inner_product vs transform_reduce

```
vector<int> weights {1, 2, 3, 4, 5, 6, 7, 8};
vector<int> counts {68, 15, 4, 45, 18, 3, 2, 11};

inner_product(counts.begin(), counts.end(), weights.begin(), 0,
                  std::plus{}, std::multiply{});
```

output: **500**

```
transform_reduce(execution::par_unseq, counts.begin(), counts.end(), weights.begin(), 0,
                  std::plus{}, std::multiply{});
```

output: **500**

inner_product vs transform_reduce

```
vector<float> weights {1e-6f, 2.1e-5f, 3.f, 43.3f, 5.1e3f, 6.5e4f, 7.7e6f, 1.5e8f};
vector<int> counts {68, 15, 4, 45, 18, 3, 2, 11};

inner_product(counts.begin(), counts.end(), weights.begin(), 0);
```

output: **1 665 688 704 g**

output with double: **1 665 688 761 g**

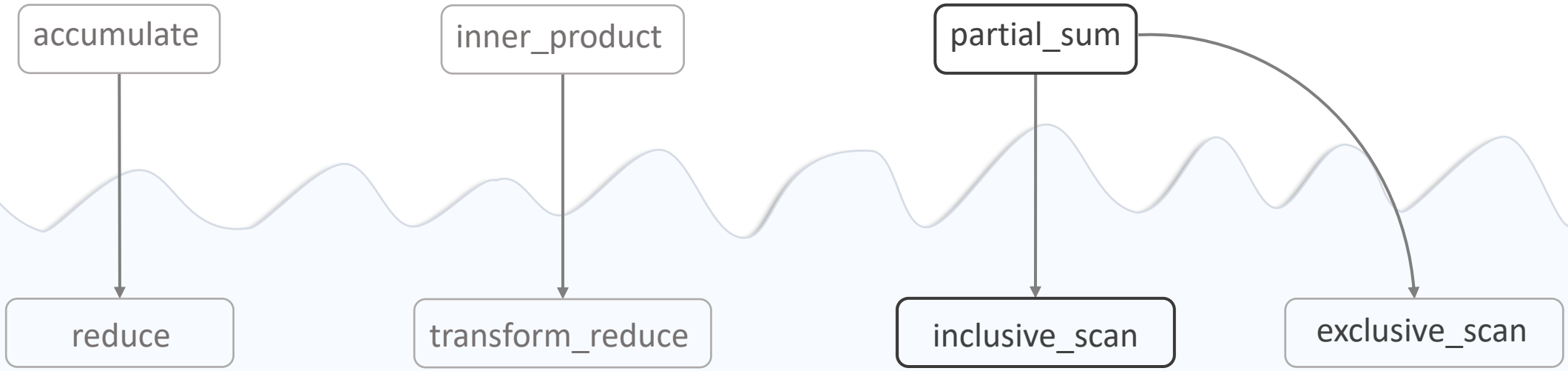
```
transform_reduce(execution::par_unseq, counts.begin(), counts.end(), weights.begin(), 0);
```

output: **1 665 688 832 g**

output with double: **1 665 688 761 g**

New algorithms introduced

All of them are here as an alternative to existing sequential only solution



partial_sum vs inclusive_scan

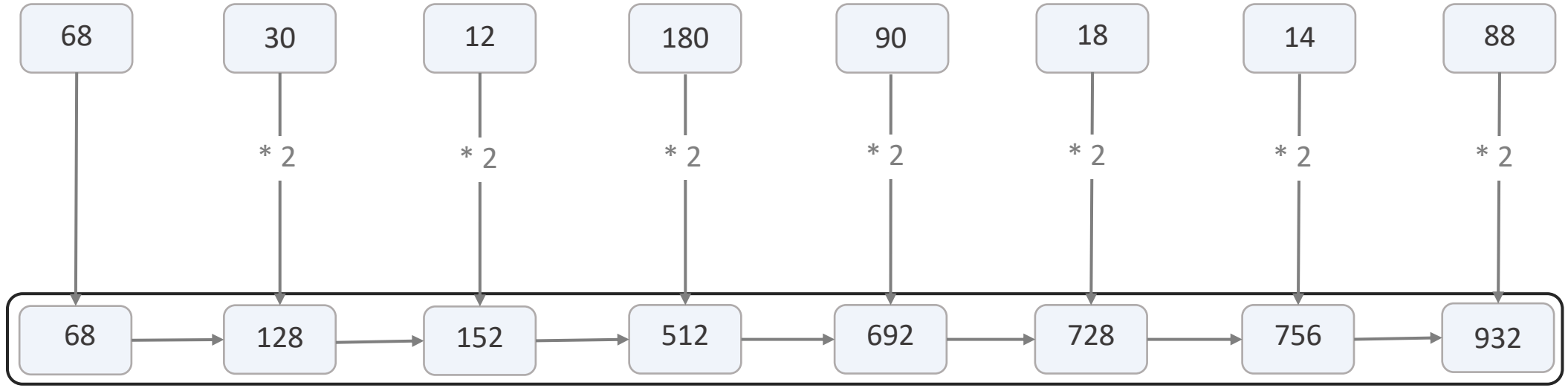
```
array<int, 8> mass {68, 30, 12, 180, 90, 18, 14, 88};
array<int, 8> food_mass;
int           growth_factor = 2;

partial_sum(mass.begin(), mass.end(), food_mass.begin(),
    [growth_factor](auto& smaller_food, auto& equal_food){
         return equal_food * growth_factor + smaller_food;
});
```

output: **68, 128, 152, 512, 692, 728, 756, 932**

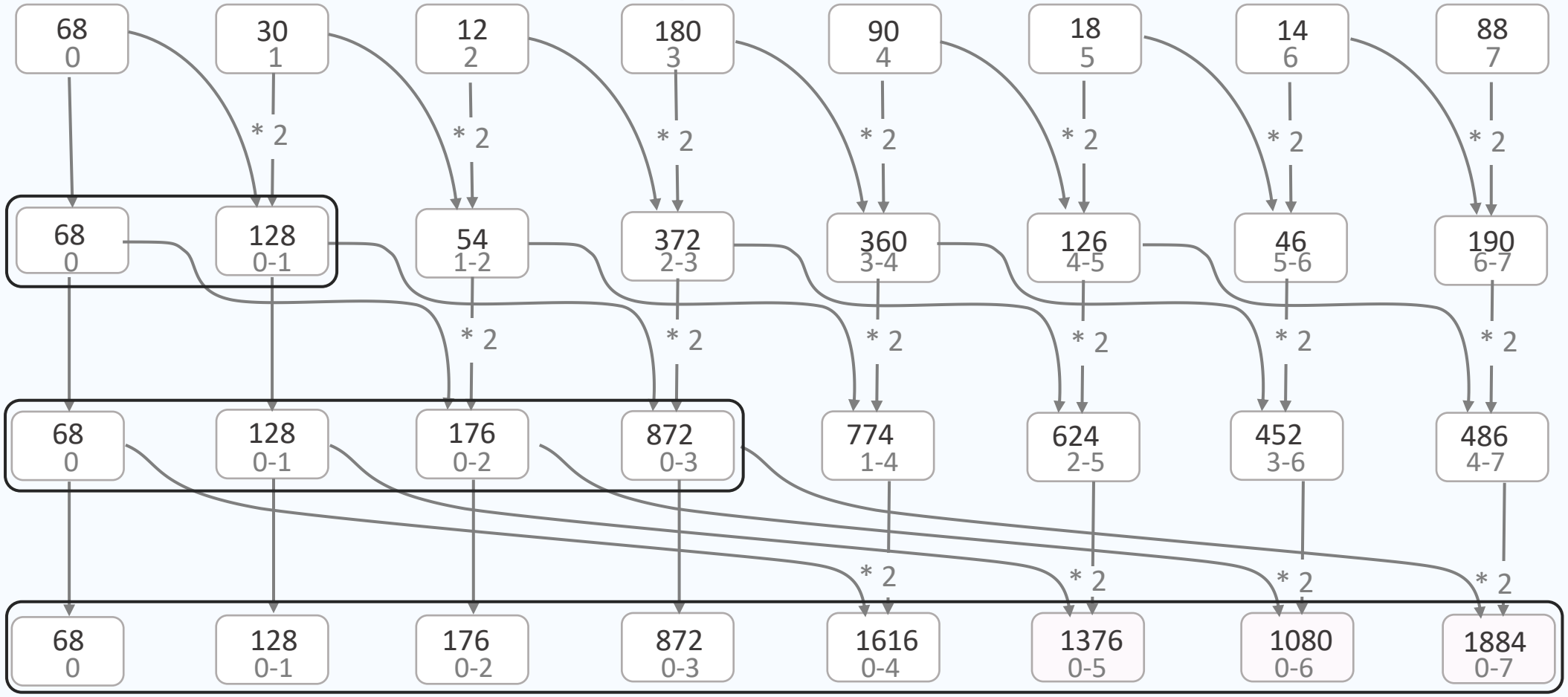
```
inclusive_scan(execution::par_unseq, mass.begin(), mass.end(), food_mass.begin(),
    [growth_factor](auto& smaller_food, auto& equal_food){
         return equal_food * growth_factor + smaller_food;
});
```

output: **68, 128, 176, 872, 1616, 1376, 1080, 1884**

partial_sum walktrough



naïve inclusive_scan walktrough



partial_sum vs inclusive_scan

```
array<int, 8> mass {68, 30, 12, 180, 90, 18, 14, 88};
array<int, 8> food_mass;
int           growth_factor = 2;

partial_sum(mass.begin(), mass.end(), food_mass.begin(),
    [growth_factor](auto& smaller_food, auto& equal_food){
         return equal_food * growth_factor + smaller_food;
});
```

output: **68, 128, 152, 512, 692, 728, 756, 932**

```
inclusive_scan(execution::par_unseq, mass.begin(), mass.end(), food_mass.begin(),
    [growth_factor](auto& smaller_food, auto& equal_food){
         return equal_food * growth_factor + smaller_food;
});
```

output: **68, 128, 176, 872, 1616, 1376, 1080, 1884**

partial_sum vs inclusive_scan

```
array<int, 8> mass {68, 30, 12, 180, 90, 18, 14, 88};
array<int, 8> food_mass;
int           growth_factor = 2;

partial_sum(mass.begin(), mass.end(), food_mass.begin(),
    [growth_factor](auto& smaller_food, auto& equal_food){
         return equal_food * growth_factor + smaller_food;
});
```

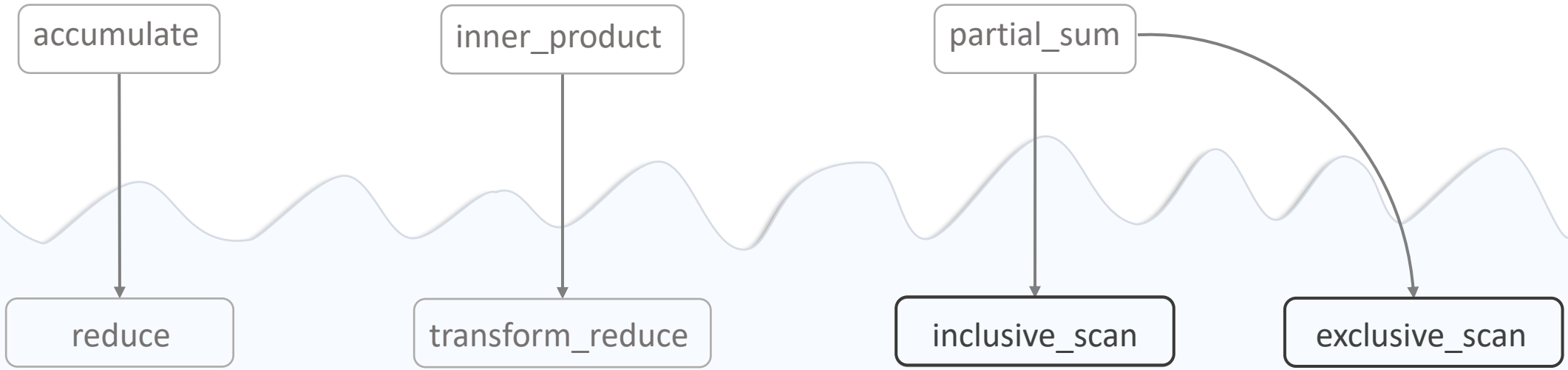
output: **68, 128, 152, 512, 692, 728, 756, 932**

```
transform_inclusive_scan(execution::par_unseq, mass.begin(), mass.end(), food_mass.begin(), std::plus{},
    [growth_factor](auto& cnt){
         return cnt * growth_factor;
});
```

output: **136, 196, 220, 580, 760, 796, 824, 1000** = **68** + 68, **128** + 68, **152** + 68, **512** + 68, **692** + 68, **728** + 68, **756** + 68, **932** + 68

New algorithms introduced

All of them are here as an alternative to existing sequential only solution



inclusive_scan vs exclusive_scan

```
array<int, 8> mass {136, 60, 24, 360, 180, 36, 28, 176};
array<int, 8> food_mass;

inclusive_scan(mass.begin(), mass.end(), food_mass.begin());
```

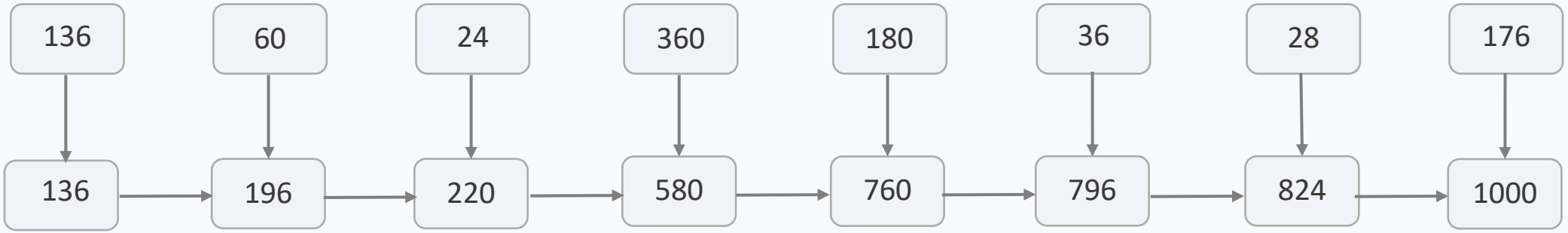
output: **136, 196, 220, 580, 760, 796, 824, 1000**

```
exclusive_scan(mass.begin(), mass.end(), food_mass.begin(), 0);
```

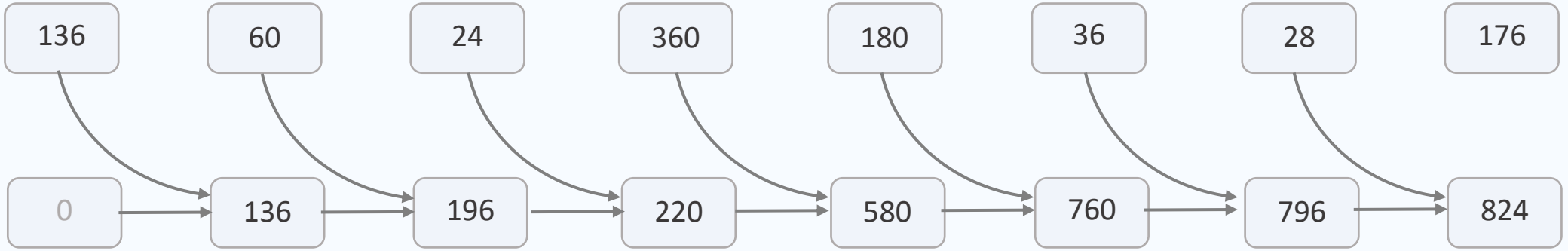
output: **0, 136, 196, 220, 580, 760, 796, 824**

inclusive_scan vs exclusive_scan

inclusive_scan:



exclusive_scan:



partial_sum vs inclusive_scan

```
array<int, 8> mass {68, 30, 12, 180, 90, 18, 14, 88};
array<int, 8> food_mass;
int           growth_factor = 2;

partial_sum(mass.begin(), mass.end(), food_mass.begin(),
    [growth_factor](auto& smaller_food, auto& equal_food){
         return equal_food * growth_factor + smaller_food;
});
```

output: **68, 128, 152, 512, 692, 728, 756, 932**

```
transform_inclusive_scan(execution::par_unseq, mass.begin(), mass.end(), food_mass.begin(), std::plus{},
    [growth_factor](auto& cnt){
         return cnt * growth_factor;
});
```

output: **136, 196, 220, 580, 760, 796, 824, 1000**

partial_sum vs inclusive_scan

```
array<int, 8> mass {68, 30, 12, 180, 90, 18, 14, 88};
array<int, 8> food_mass;
int           growth_factor = 2;

partial_sum(mass.begin(), mass.end(), food_mass.begin(),
    [growth_factor](auto& smaller_food, auto& equal_food){
         return equal_food * growth_factor + smaller_food;
});
```

output: **68, 128, 152, 512, 692, 728, 756, 932**

```
transform_exclusive_scan(execution::par, mass.begin() + 1, mass.end(), food_mass.begin(), mass[0], std::plus{},
    [growth_factor](auto& cnt){
         return cnt * growth_factor;
});
```

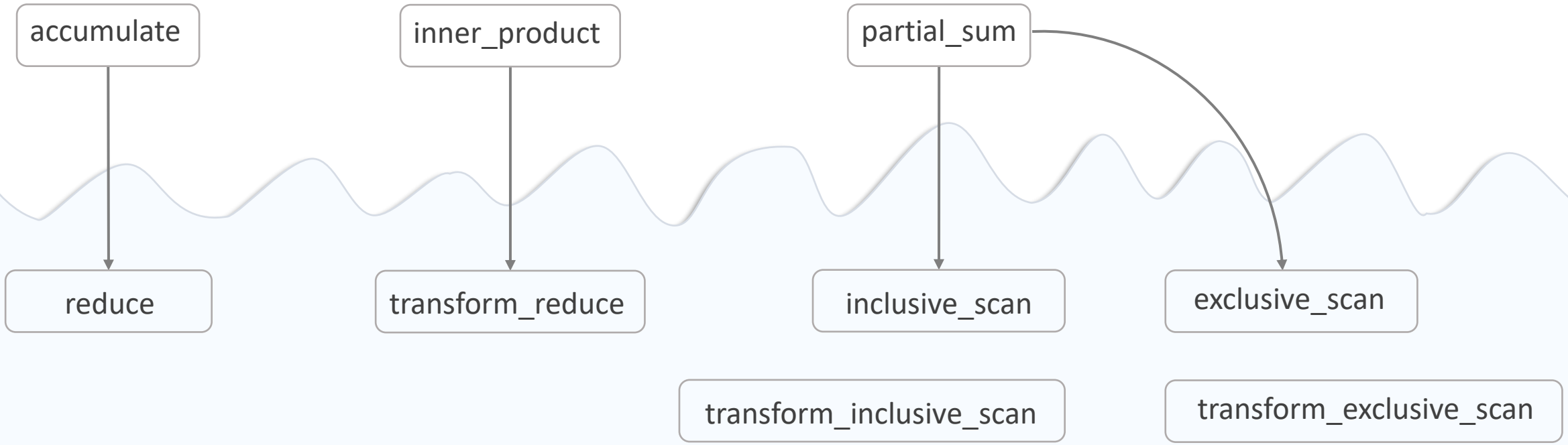
output: **68, 128, 152, 512, 692, 728, 756, ?**

New algorithms introduced

Always prefer **reduce**, **inclusive_scan**, **exclusive scan** and their transformed version if possible

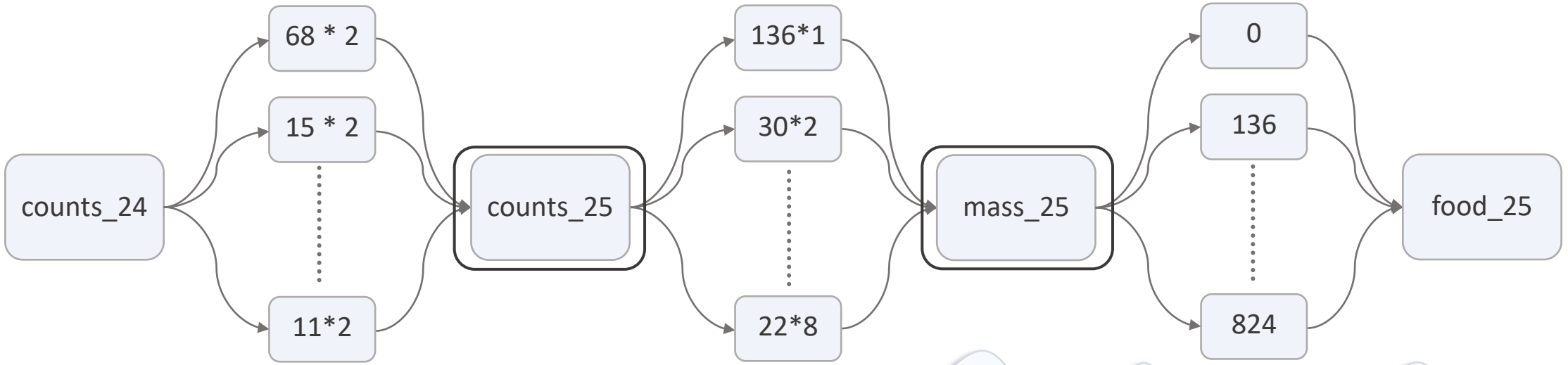
Use **accumulate**, **inner_product** and **partial_sum** only for non-associative operations

Be aware of floating point non-associativity

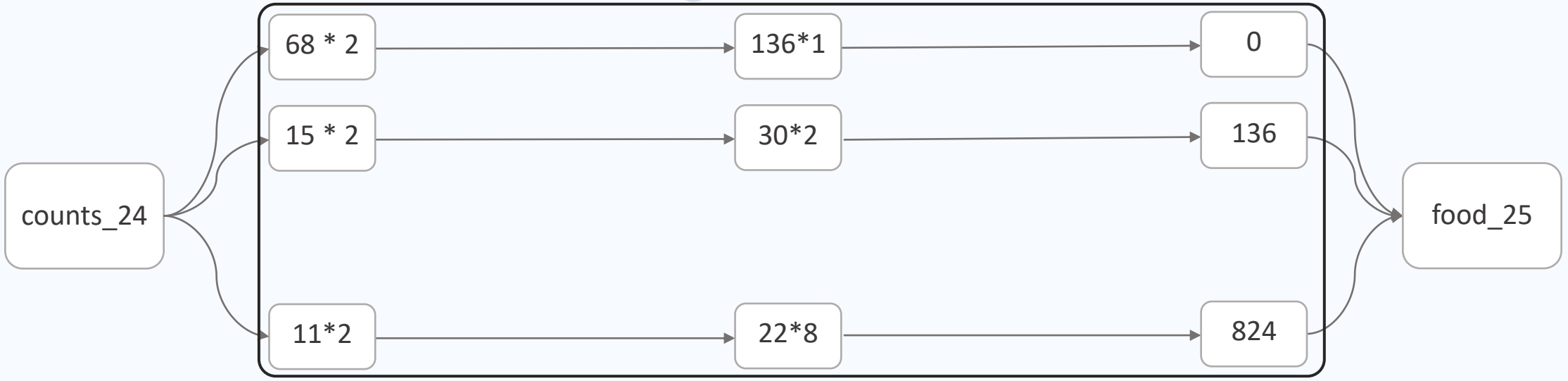


Unwanted synchronization points

```
array<int, 8> counts_24 {68, 15, 4, 45, 18, 3, 2, 11};
array<int, 8> weights {1, 2, 3, 4, 5, 6, 7, 8};

transform(par_unseq, counts_24.begin(), counts_24.end(), counts_25.begin(), [](auto cnt){return cnt * 2;});
transform(par_unseq, counts_25.begin(), counts_25.end(), weights.begin(), mass_25.begin(), multiplies{});
exclusive_scan(par_unseq, mass_25.begin(), mass_25.end(), food_25.begin(), 0);
```



Unwanted synchronization points




```
auto mass_24 = views::zip_transform(multiplies{}, counts_24, weights);
```

```
transform_exclusive_scan(par_unseq, mass_24.begin(), mass_24.end(), food_25.begin(), 0,
                         plus{}, ([&](auto item){return item * 2;}));
```

Parallel algorithms

All the rest of the standard library algorithms could be used in parallel version

Some of them may require additional allocation

Some of them are not possible to efficiently vectorize

And some may not be implemented so far

But don’t worry the worst you can get is sequential performance you already had before

All you need to do is to add an execution policy

Execution policy

First param of each parallel algorithm

Defines how much is it possible to parallelize code inside algorithm body

For the best results go for the strongest policy you can

The stronger policy you get, the more limited you are inside the algorithm body

If you are unable to use strongest one, maybe you won’t gain from parallelization

Always measure performance before and after parallelization

Execution policy

std::execution::seq for sequenced policy

std::execution::par for parallel policy

std::execution::unseq for parallel unsequenced policy

std::execution::par_unseq for unsequenced policy

execution::seq

Code is executed sequentially

All computations are executed on single thread one by one

No parallelization at all

If there is no policy defined it runs in execution::seq

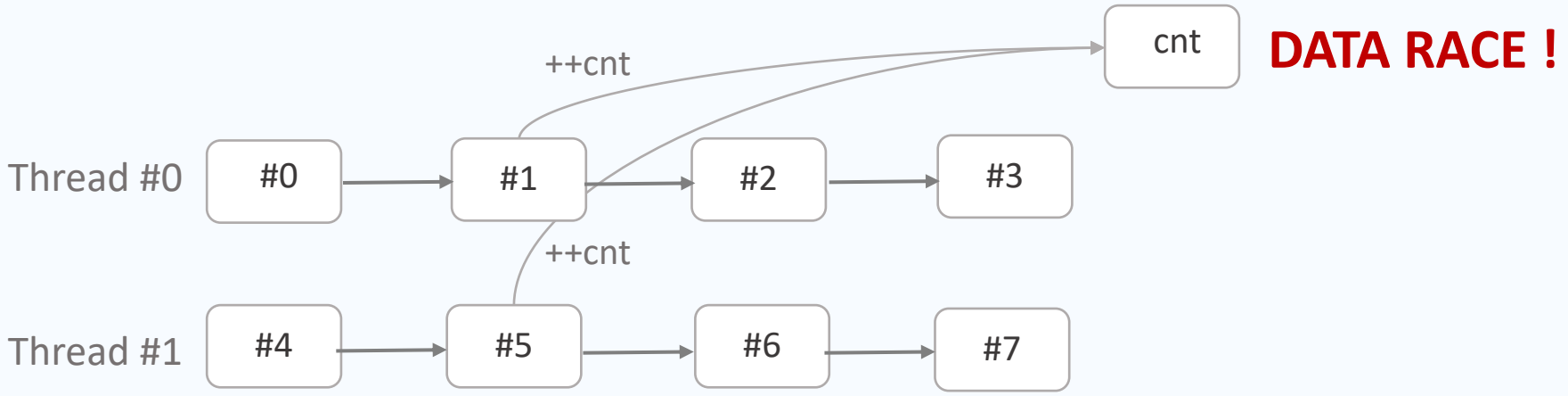
execution::par

Code is executed on multiple threads

Order in which are elements processed is not predictable

Shared data needs to be protected as they may be accessed by different threads concurrently

If blocking protection is needed it may not perform better than sequential approach – don’t forget to measure it



DATA RACE !

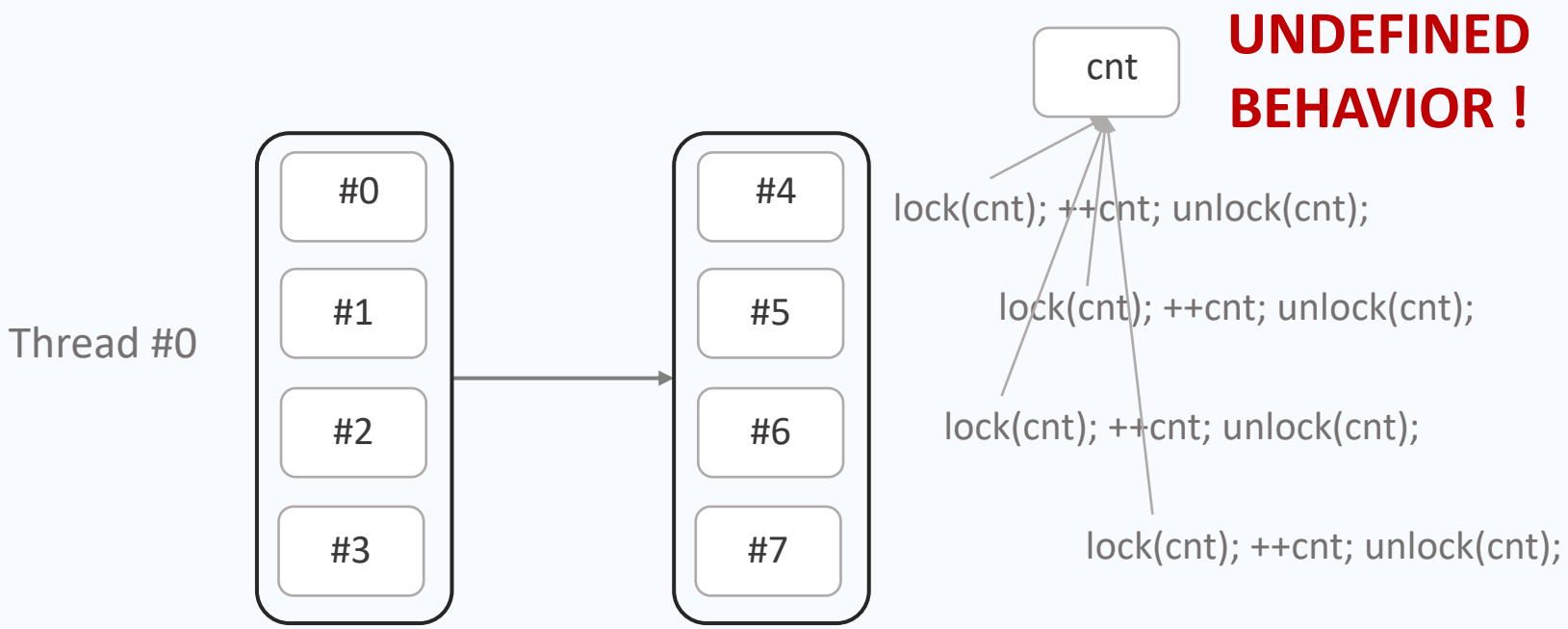
execution::unseq

Code is executed in single thread

Whole vector of data is executed together – their instruction are in unpredictable order

No synchronization is allowed

No, not even atomics



execution::par_unseq

Data are vectorized and executed on multiple threads

Strongest possible version of parallelization

Keeps the same limitation as unseq – no synchronization is allowed

If your code may run on unseq it may run on par_unseq there is no difference in rules

You should try to target this policy

cnt

DON'T EVEN THINK ABOUT IT

Plenty of fish in the sea

```
struct Fish  { int pos; int velocity; };
vector<Fish> fishes{…};
auto         time_interval = 1;


for_each(execution::par_unseq, fishes.begin(), fishes.end(), [&](auto& fish)
{
    fish.pos += time_interval * fish.velocity;
});
```

Beware of shark

```
struct Fish  { int pos; int velocity;};
vector<Fish> fishes{…};
auto         time_interval = 1;
atomic<bool> shark = false;              //shark is handled somewhere else and this will signal his presence

for_each(execution::par, fishes.begin(), fishes.end(), [&](auto& fish)
{
    if(shark)
         fish.run_away();
    else
         fish.pos += time_interval * fish.velocity;
});
```

Look for a hideout

```
struct Hideout {int pos; int slots; };
vector<Hideout> hideouts{…};

for_each(execution::par_unseq, fishes.begin(), fishes.end(), [&](auto& fish)
{
    auto safety = filter_view(hideouts, [](auto& hideout){ return hideout.slots > 0;});
    auto closest = adjacent_find(safety.begin(), safety.end(), [&](auto& first, auto& second) {
         return (first.pos < fish.pos && second.pos >= fish.pos)});

    auto& selected = choose_closer_neighbor(closest);

    swim_for(std::abs(selected->pos - fish.pos) * fish.velocity);

    if(selected->take_slot())
         stay_hidden();
    else
         try_mimicry();
});
```

Look for a hideout

```
struct Hideout {int pos; int slots_cnt(); bool take_slot(); private: int slots; mutex slot_mutex; };
vector<Hideout> hideouts{…};

for_each(execution::par, fishes.begin(), fishes.end(), [&](auto& fish)
{
    auto safety = filter_view(hideouts, [](auto& hideout){ return hideout.slots_cnt());
    auto closest = adjacent_find(safety.begin(), safety.end(), [&](auto& first, auto& second) {
         return (first.pos < fish.pos && second.pos >= fish.pos)});

    auto& selected = choose_closer_neighbor(closest);

    swim_for(std::abs(selected->pos - fish.pos) * fish.velocity);

    if(selected->take_slot())
         stay_hidden();
    else
         try_mimicry();
});
```

Become a leader

```
bool has_leader = false;
mutex leaders_mutex;
vector<Fish> fishes;

for_each(execution::par_unseq, fishes.begin(), fishes.end(), [&](auto& fish)
{
    unique_lock lock(leaders_mutex);
    while(has_leader){
        lock.unlock(); swim_around(); lock.lock();
    }
    has_leader = true;
    lock.unlock();

    live_leaders_life();

    lock.lock();
    has_leader = false;
});
```

```
unique_lock lock(leaders_mutex);
unique_lock lock(leaders_mutex);
unique_lock lock(leaders_mutex);
unique_lock lock(leaders_mutex);
```

UNDEFINED BEHAVIOR !

Become a leader

```
atomic<bool> has_leader = false;
vector<Fish> fishes;


for_each(execution::par_unseq, fishes.begin(), fishes.end(), [&](auto& fish)
{
    while(has_leader.exchange(true))
         swim_around();

    live_leaders_life();

    has_leader = false;
});
```

```
while(has_leader.exchange(true))
     swim_around();

live_leaders_life();


while(has_leader.exchange(true))
    swim_around();
```

DEADLOCK!

Summary

Use standard library algorithms – your life will be easier

Use the strongest possible policy

Try to avoid data dependencies – synchronization impact is huge

Always measure your performance

Beware of non-associative operations

Avoid synchronization points by utilizing views

Deeper insight

Think Parallel (by Bryce Adelstein Lelbach)

The C++ Execution Model (by Bryce Adelstein Lelbach)

Portable floating-point calculations (by Guy Davidson)

Parallel STL https://github.com/llvm/llvm-project/tree/main/pstl

Thrust https://github.com/NVIDIA/cccl/tree/main/thrust

Sources

All examples and naive algorithms as presented

https://github.com/EmptySquareBubble/Stories_from_a_parallel_universe

Thank you!