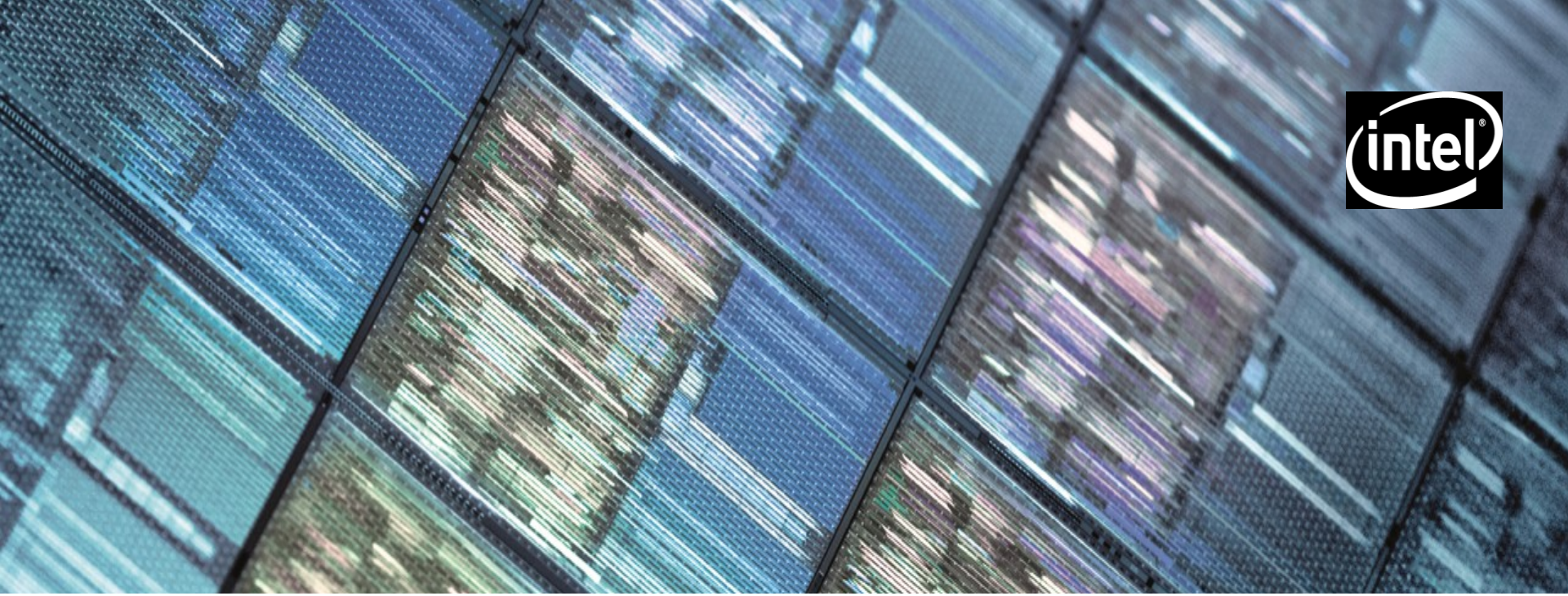

Structured Parallel Programming with Deterministic Patterns

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Patterns

*A **parallel pattern** is a commonly occurring combination of task distribution and data access*

- Many common programming models support either only a small number of patterns, or only low-level hardware mechanisms
  - So often common patterns implemented only as "conventions"

Observation: a small number of patterns, most of them deterministic, can support a wide range of applications

Thesis: A system that ***directly*** supports these deterministic patterns and allows their composition can generate efficient implementations on a variety of hardware architectures

Motivation for Pattern-based Design

Deterministic patterns → higher maintainability

- No need to debug race conditions if it not possible to create them
- Allow introduction of races only where necessary, and limit scope
- Determinism and consistency with single serial execution order simplifies user understanding, debugging and testing

Application oriented patterns → higher productivity

- Patterns derived from common use cases in applications
  - Subset of patterns are universal: gives wide applicability
  - Patterns can also target specific domains:
    - Makes simple things simple
- Patterns encourage high-level reasoning
  - Focus users on what really matters: parallelism and data locality
  - Simplifies learning how to write efficient programs

Serial Patterns

*The following patterns are the basis of "**structured programming**" for serial computation:*

- Sequence
- Selection
- Iteration
- Recursion
- Random read
- Random write
- Stack allocation
- Heap allocation
- Objects/closures

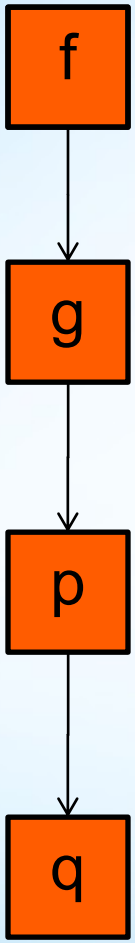
Compositions of control flow patterns can be used in place of unstructured mechanisms such as "goto."

Parallel Patterns

*The following additional parallel patterns can be used for "**structured parallel programming**":*

- Superscalar sequence
- Speculative selection
- Map
- Recurrence/scan
- Reduce
- Pack/expand
- Nest
- Pipeline
- Partition
- Stencil
- Search/match
- Gather
- **Permutation scatter*
- **Merge scatter*
- *!Atomic scatter*
- Priority scatter

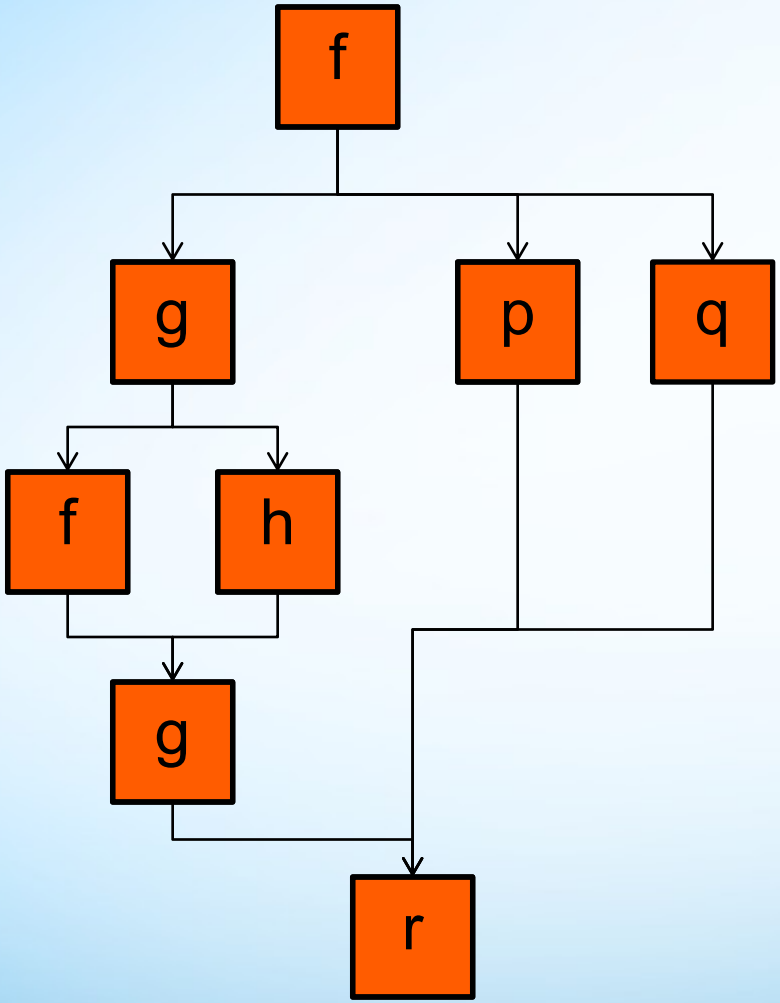
Sequence



A serial sequence is executed in the exact order given:

```
B = f(A);
C = g(B);
E = p(C);
F = q(A);
```

Superscalar Sequence

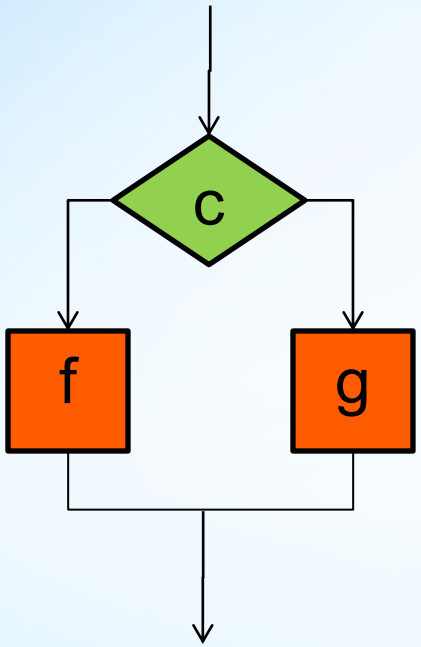


Developer writes "serial" code:

```
B = f(A);
C = g(B);
E = f(C);
F = h(C);
G = g(E,F);
P = p(B);
Q = q(B);
R = r(G,P,Q);
```

- However, tasks only need to be ordered by data dependencies
- Depends on limiting scope of data dependencies

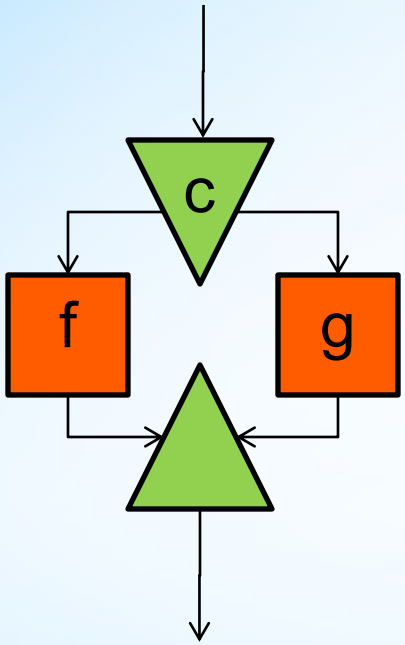
Selection



The condition is evaluated first, then one of two tasks is executed based on the result.

```
IF (c) {
    f
} ELSE {
    g
}
```

Speculative Selection



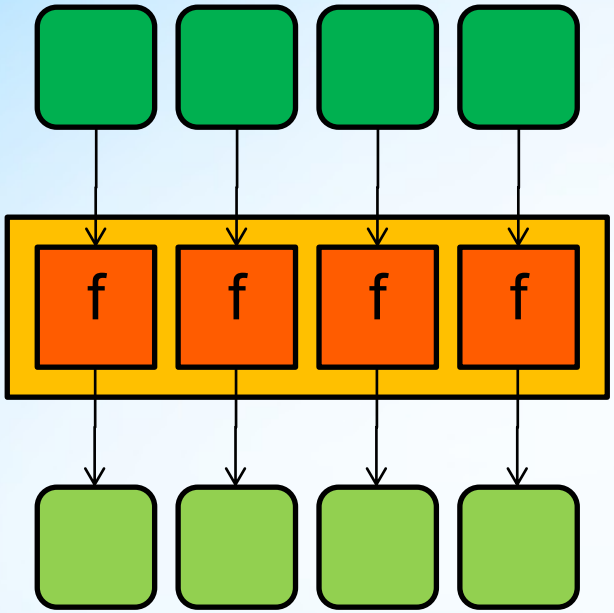
Both sides of a conditional and the condition are evaluated in parallel, then the unused branch is cancelled.

```
SELECT (c) {
    f
} ELSE {
    g
}
```

- Effort in cancelled task "wasted"
- Use only when a computational resource would otherwise be idle, or tasks are on critical path

Examples: collision culling; ray tracing; clipping; discrete event simulation; search

Map



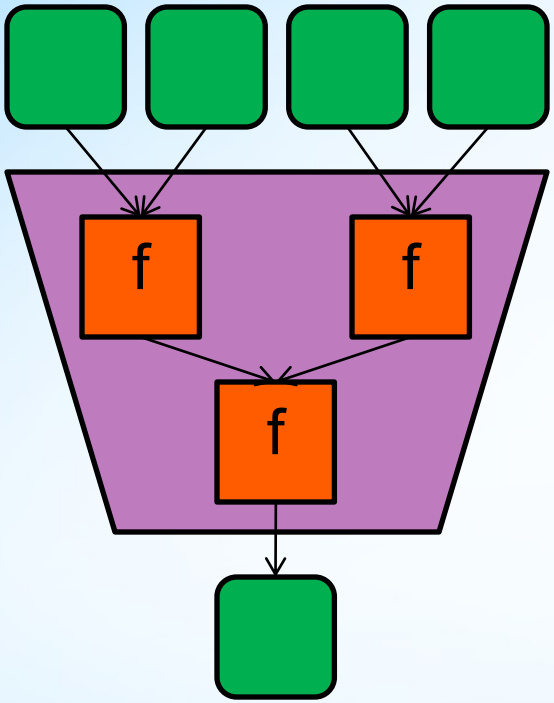
- Map replicates a function over every element of an index set (which may be abstract or associated with the elements of an array).

```
A = map(f,B);
```

- This replaces one specific usage of iteration in serial programs: processing every element of a collection with an independent operation.

Examples: gamma correction and thresholding in images; color space conversions; Monte Carlo sampling; ray tracing.

Reduction



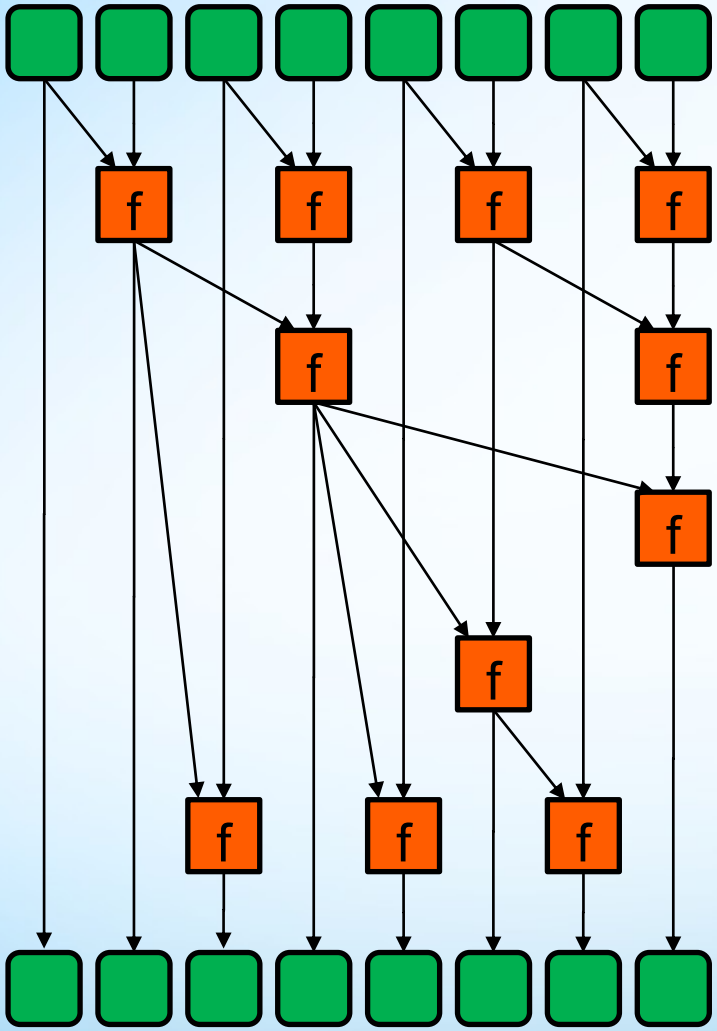
- Reduce combines every element in a collection into one element using an associative operator.

```
b = reduce(f,B);
```

- For example, reduce can be used to find the sum or maximum of an array.
- There are some variants that arise from combination with *partition* and *search*

Examples: averaging of Monte Carlo samples; convergence testing; image comparison metrics; sub-task in matrix operations.

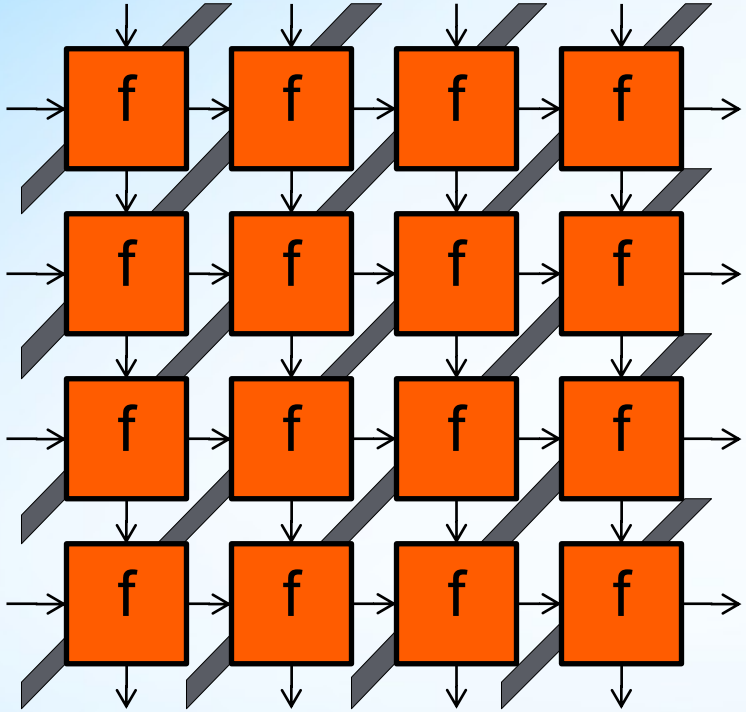
Scan



- Scan computes *all* partial reductions
- Allows parallelization of many 1D recurrences
- Requires an associative operator
- Requires 2n work over serial execution, but lg n steps

Examples: integration, sequential decision simulations in financial engineering, can also be used to implement pack

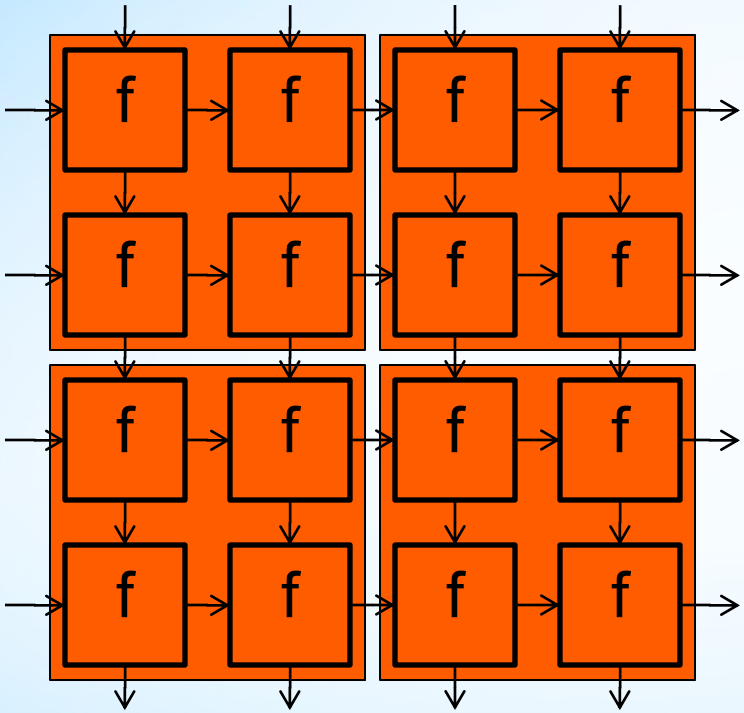
Recurrences



Examples: infinite impulse response filters; sequence alignment (Smith-Waterman dynamic programming); matrix factorization

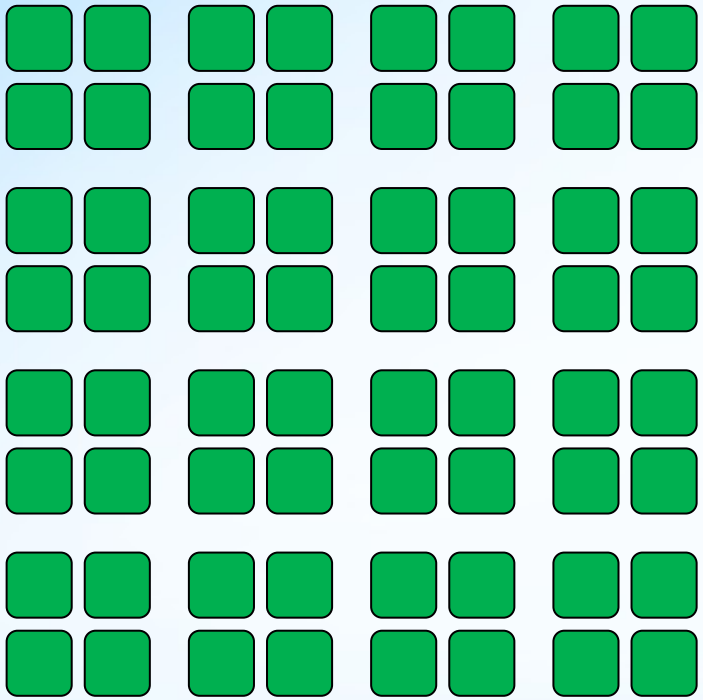
- Recurrences arise from the data dependency pattern given by *nested* loop-carried dependencies.
  - nD recurrences can *always* be parallelized over n-1 dimensions by Lamport's hyperplane theorem
- Execution of parallel slices can be performed either via iterative map or via wavefront parallelism

Recurrences: Implementation Note



- Implementation can use blocking for higher performance
- When combined with the "pipeline" pattern recurrences implements "wavefront" computation
- Can also be combined with superscalar execution (see recent ICS paper…)

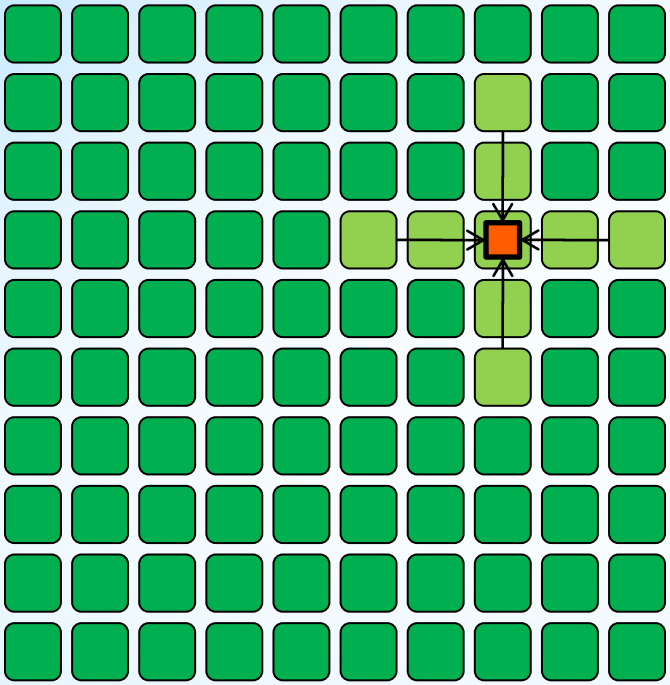
Partition



Examples: JPG and other macroblock compression; divide-and-conquer matrix multiplication; coherency optimization for cone-beam reconstruction

- Partition breaks an input collection into a collection of collections
- Useful for divide-and-conquer algorithms
- Variants:
  - Uniform: dice
  - Non-uniform: segment
  - Overlapping: tile
- Issues:
  - How to deal with boundary conditions?
- Partitions don't move data, they just provide an alternative "view" of its organization

Stencil

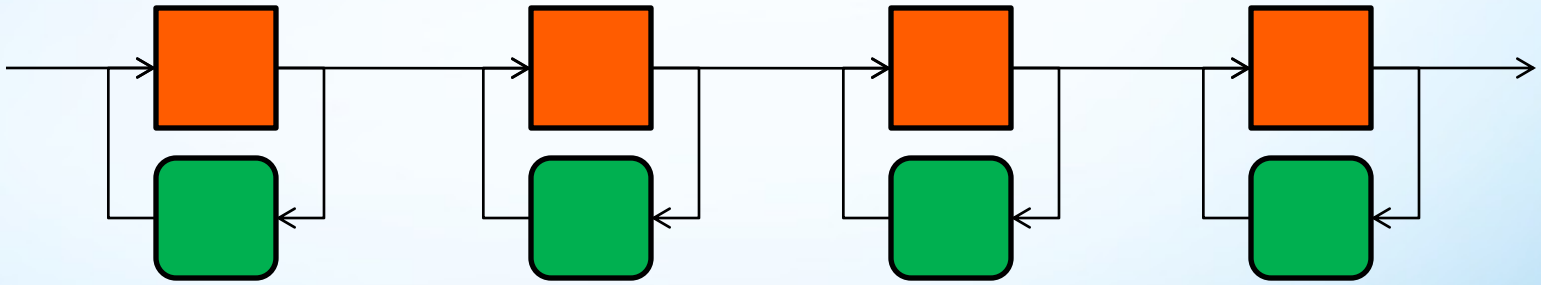


- Apply function to all neighbourhoods of an array
- Neighbourhoods given by set of relative offsets
- Optimized implementation requires blocking and sliding windows
- "Boundary modes" on array accesses useful

Examples: image filtering including convolution, median, anisotropic diffusion; simulation including fluid flow, electromagnetic, and financial PDE solvers, lattice QCD

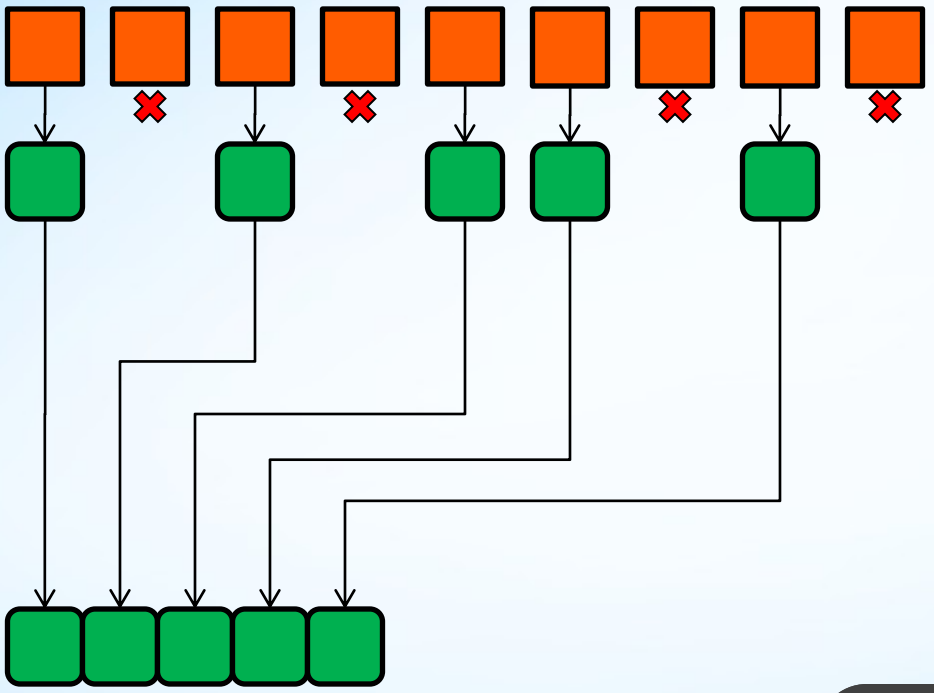
Pipeline

- Tasks can be organized in chain with *local state*
- Useful for serially dependent tasks like codecs
- Whole chain applied like map to collection or *stream*
- Implementation of many sub-patterns may be optimized for pipeline execution when inside this pattern



Examples: codecs with variable-rate compression; video processing; spam filtering.

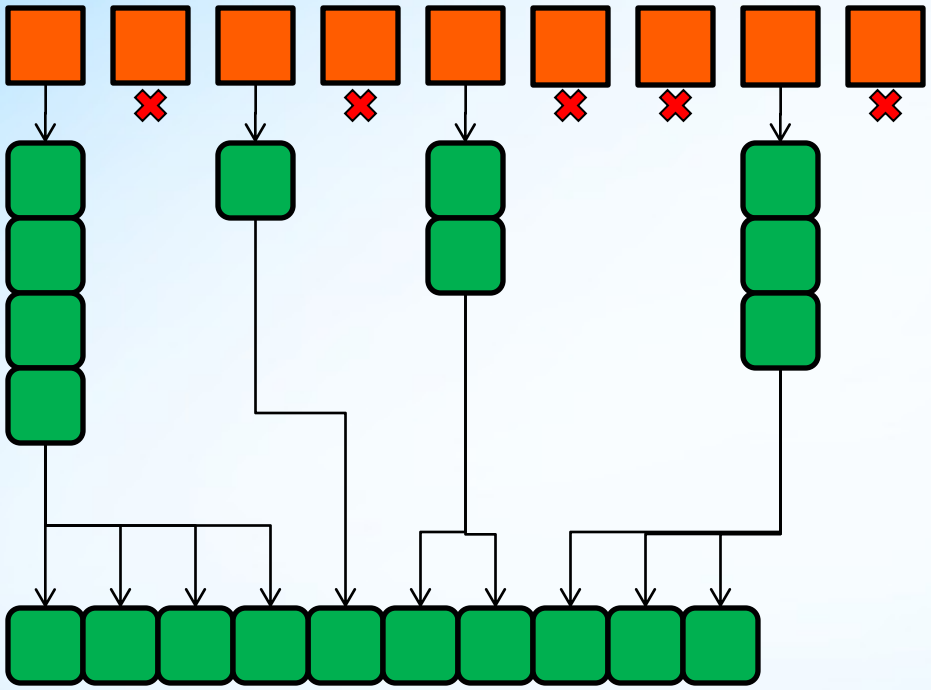
Pack



- Pack allows deletion of elements from a collection and elimination of unused space
- Useful when fused with map and other patterns to avoid unnecessary output

Examples: narrow-phase collision detection pair testing (only want to report valid collisions), peak detection for template matching.

Expand



- Expand allows element of map operation to insert any number of elements (including none) into its output stream
- Useful when fused with map and other patterns to support variable-rate output

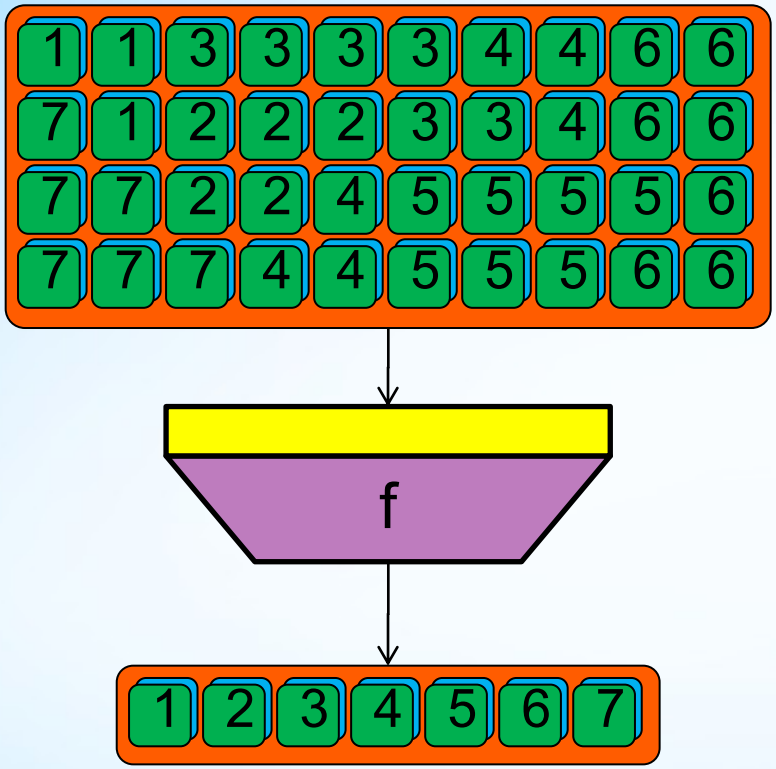
Examples: broad-phase collision detection pair testing (want to report potentially colliding pairs); compression and decompression.

Fused Patterns

- Programs are built from combinations of patterns
- Should be able to fuse patterns for performance
- May be useful to explicitly support specific combinations

- Examples:
  - Gather = map + random read
  - Scatter = map + random write
  - Map + reduce for preprocessing before reduction
  - Map + pack/expand for culling operations
  - Partition + reduce for multidimensional reduction

Search/Match



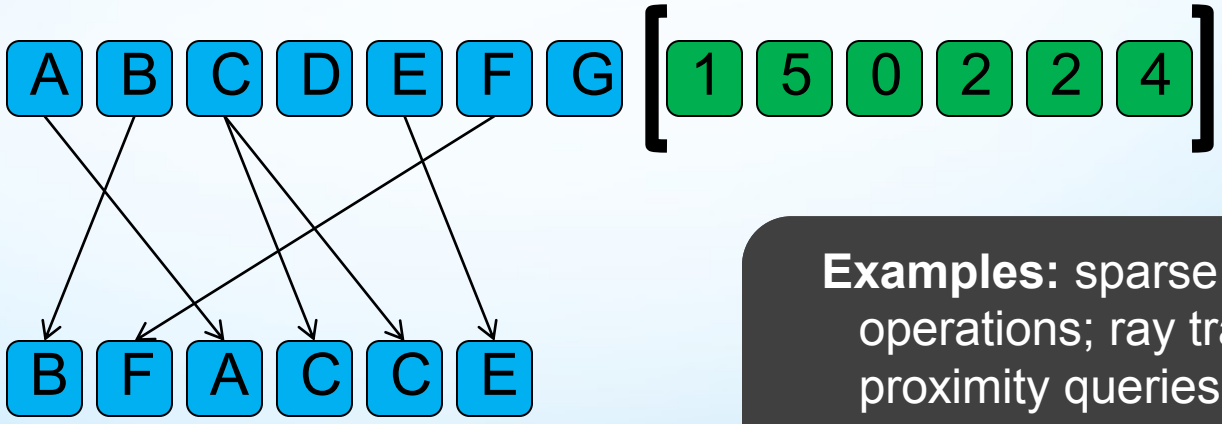
Examples: computation of metrics on segmented regions in vision; computation of web analytics

- Searching and matching fundamental capabilities
- Use to select data for another operation, by creating a (virtual) collection or partitioned collection.

- Example: ***category reduction*** reduces all elements in an array with the same "label", and is the form used in Google's map-reduce

Gather

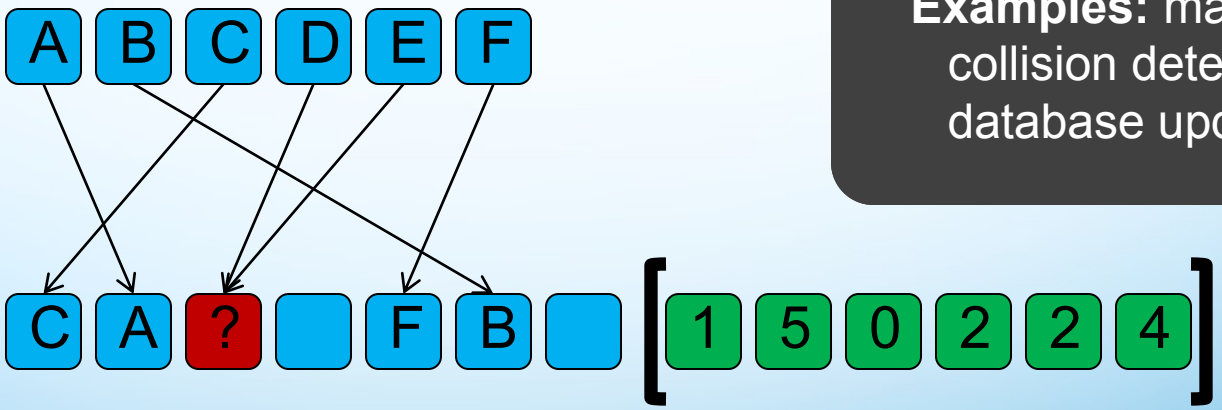
- Map + Random Read
  - Read from a random (computed) location in an array
  - When used inside a map or as a collective, becomes a parallel operation
  - Views into arrays, but no global pointers
  - Write-after-read semantics for kernels to avoid races



Examples: sparse matrix operations; ray tracing; proximity queries; collision detection.

*!Scatter

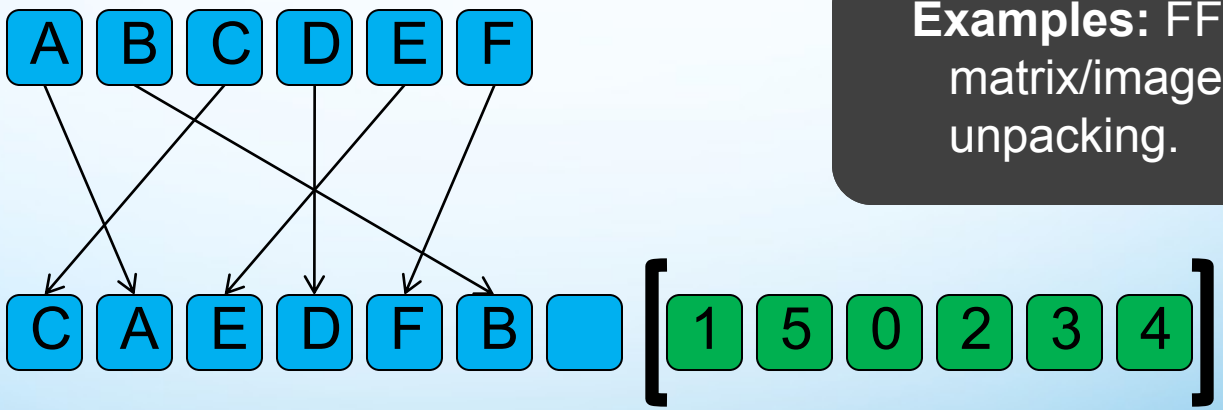
- Map + Random Write
  - Write into a random (computed) location in an array
  - When used inside a map, becomes a parallel operation
  - *Race conditions possible when there are duplicate write addresses ("collisions")*
  - To obtain deterministic scatter, need a deterministic rule to resolve collisions



Examples: marking pairs in collision detection; handling database update transactions.

*Permutation Scatter

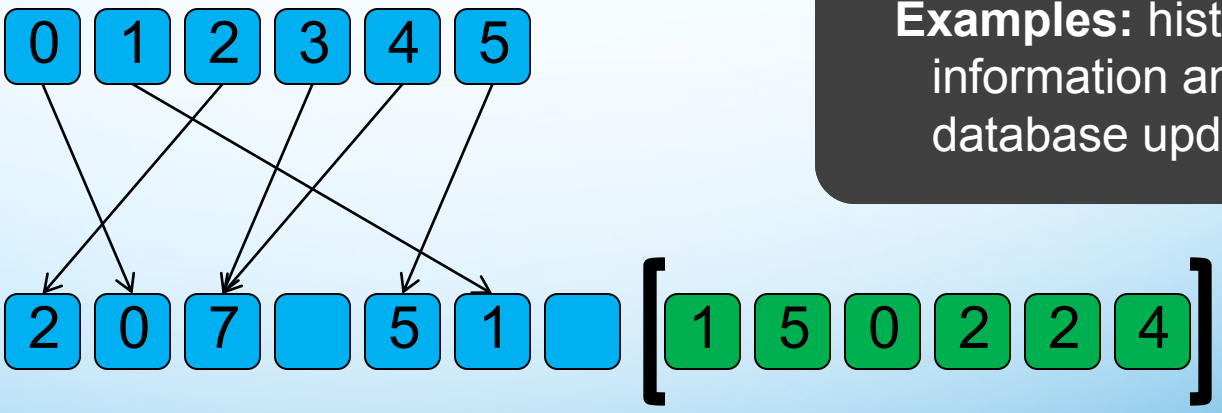
- Make collisions *illegal*
- Only guaranteed to work if no duplicate addresses
- Danger is that programmer will use it when addresses do in fact have collisions, then will depend on undefined behaviour
- Similar safety issue as with out-of-bounds array accesses.
- Can test for collisions in "debug mode"



Examples: FFT scrambling; matrix/image transpose; unpacking.

*Merge Scatter

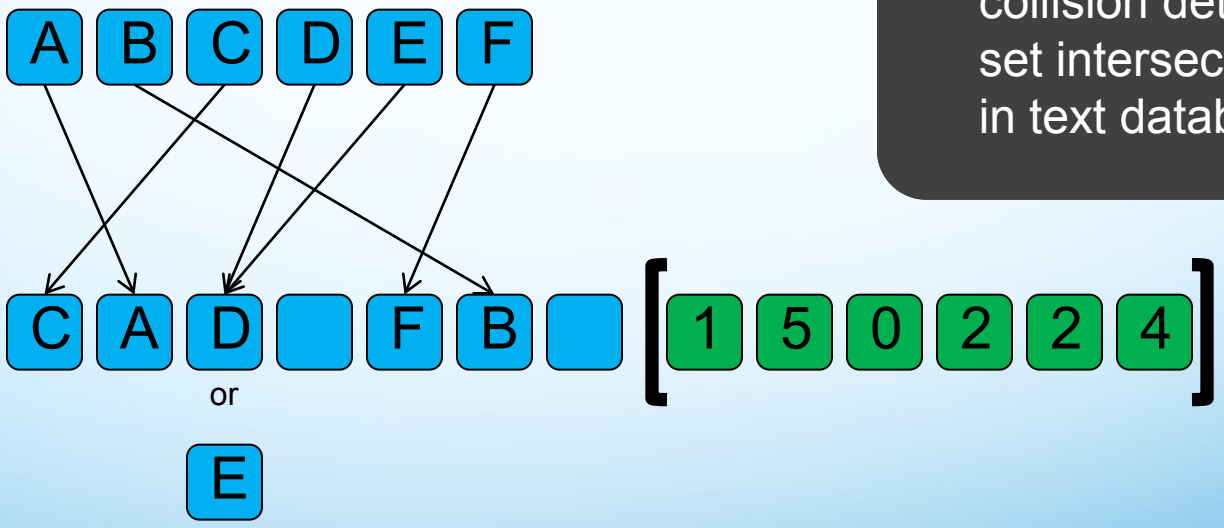
- Use an associative operator to combine values upon collision
- Problem: as with reduce, depends on programmer to define associative operator
- *Gives non-deterministic read-modify-write when used with non-associative operators*
- Due to structured nature of other patterns, can still provide tool to check for race conditions.



Examples: histogram; mutual information and entropy; database updates.

!Atomic Scatter

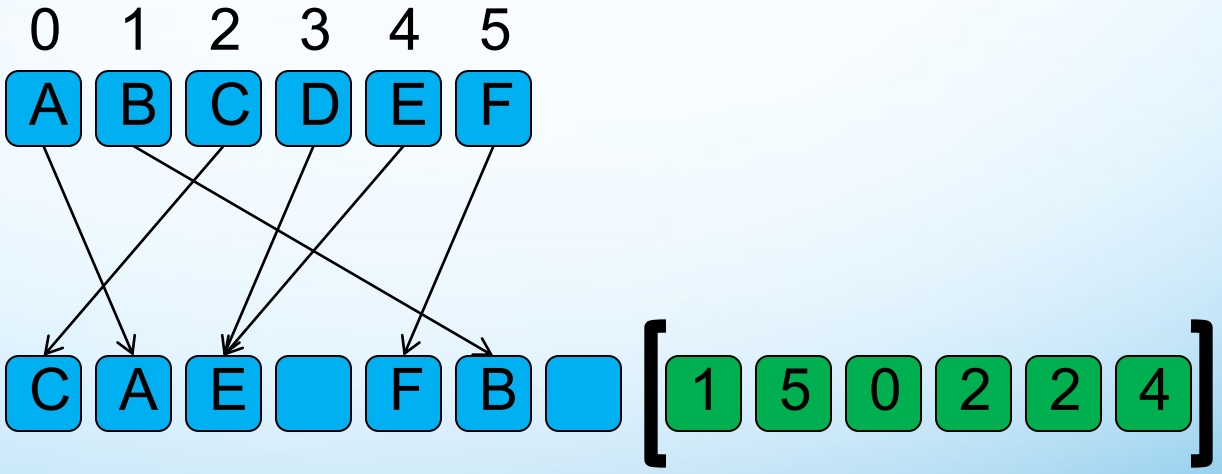
- Resolve collisions atomically but *non-deterministically*
- Use of this pattern will result in non-deterministic programs
- Structured nature of rest of patterns makes it possible to test for race conditions



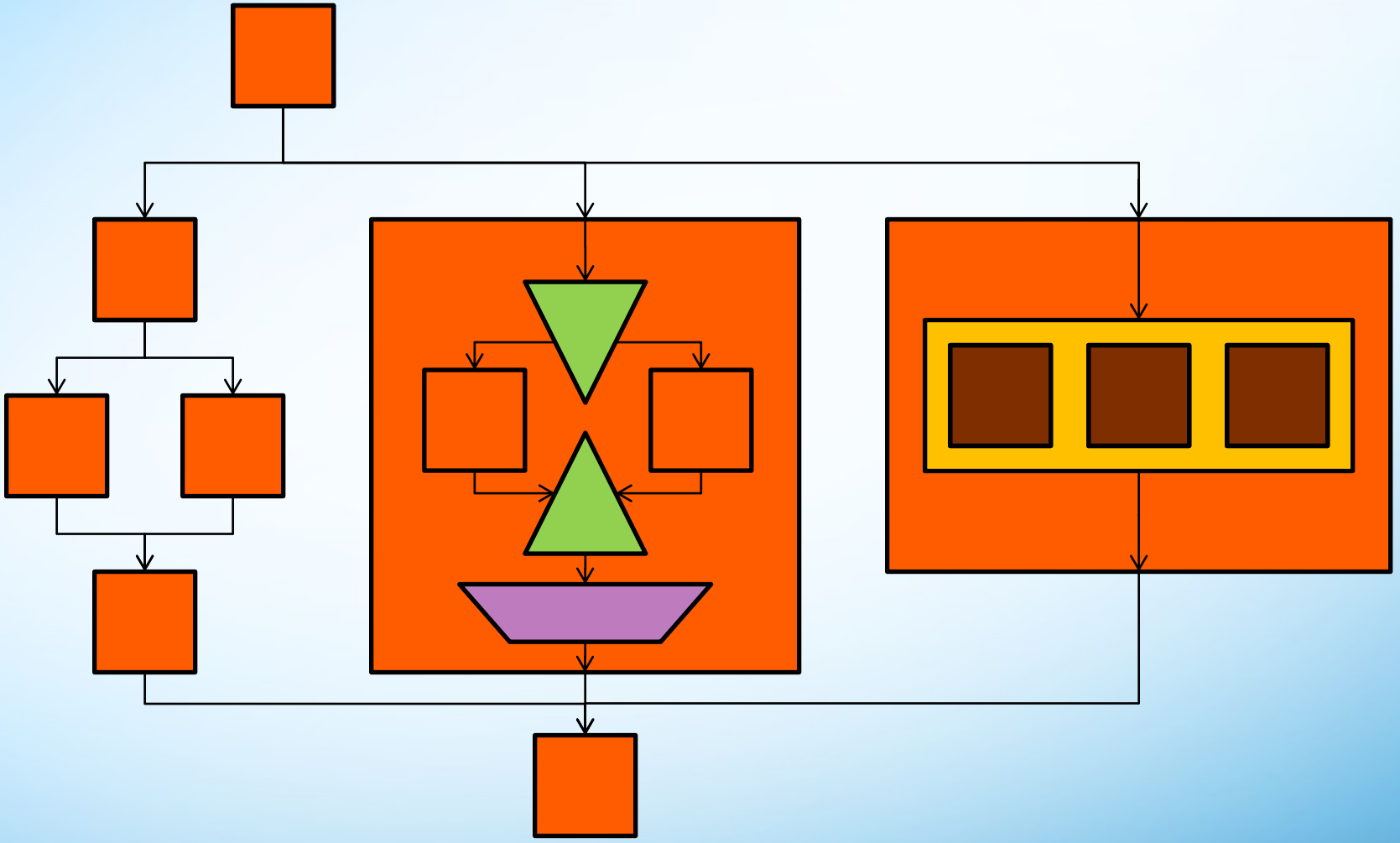
Examples: marking pairs in collision detection; computing set intersection or union (used in text databases)

Priority Scatter

- Assign every parallel element a priority
  - NOTE: Need hierarchical structure of other patterns to do this
- ***Deterministically*** determine "winner" based on priority
- When converting from serial code, priority can be based on original ordering, *giving results consistent with serial program*
- Efficient implementation is similar to hierarchical z-buffer…



Nesting



Conclusion

- Patterns can be used to reason about and organize development of parallel algorithms *and* programming models
  - Integrating these patterns into Ct for heterogeneous computing
- Many useful patterns are deterministic
- Compositions of deterministic patterns lead to deterministic programs

Discussion:

- Are there a smaller number of "primitive" patterns?
- Are any important patterns missing?
- Can "structured" be well-defined?
- How important are non-deterministic patterns?
  - Can any of these be considered "structured"?

BACKUP

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Challenge:
Multiple Parallelism Mechanisms

Modern processors have *many* kinds of parallelism:

- Pipelining
- SIMD within a register (SWAR) vectorization
- Superscalar instruction issue or VLIW
- Overlapping memory access with computation (prefetch)
- Simultaneous multithreading (hyperthreading) per core
- Multiple cores
- Multiple processors
- Asynchronous host and accelerator execution
- HPC adds: clusters, distributed memory, grid…

General Factors Affecting Algorithm Performance

1. **Parallelism**
   - Choose or design a good *parallel* algorithm
   - Large amount of latent parallelism, low serial overhead
   - Asymptotically efficient
   - Should scale to large number of processing elements
2. **Locality**
   - Efficient use of the memory hierarchy
     - More frequent use of faster local memory
   - Coherent use of memory and data transfer
     - Good alignment, predictable memory access; blocking
   - High arithmetic intensity