

# Subsetix: Sparse 2D Geometry on GPU

From Set Algebra to AMR Simulation

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# Outline

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# **I. Context: GPU & Kokkos**

# Project Context — Towards Exascale

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## Background

- **Numpex Project:** French initiative pushing scientific computing to exascale
- **Samurai:** AMR library with unique sparse data structure (interval-based)
- **Challenge:** No prior GPU implementation of Samurai's core concepts

## Objective

*How can Samurai's strategy evolve for exascale?*

- GPU acceleration (today's focus)
- Multi-node distribution (future work)

## Approach

### Proof of Concept Strategy

1. **Simplify** — Isolate core problems
2. **Prototype** — Build independent bricks
3. **Validate** — Test on real simulations
4. **Integrate** — Path back to Samurai

**This work:** GPU-native sparse 2D geometry as a standalone proof of concept

# GPU Architecture — Massively Parallel

## Execution Hierarchy

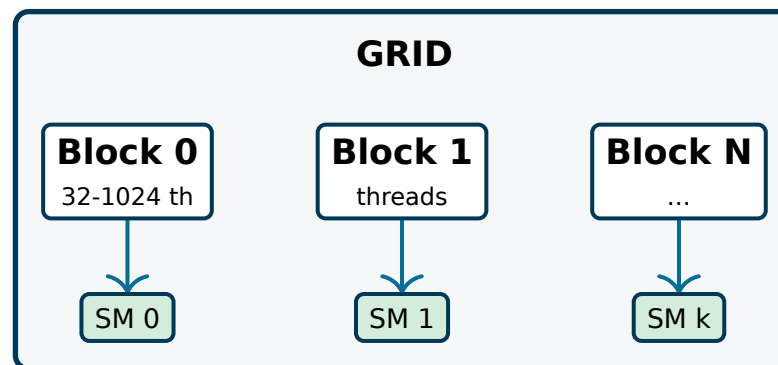


- **Warp** = 32 threads in **lockstep** (SIMT)
- **SM** = autonomous compute unit
- Multiple warps/SM → latency hiding

## For Our Project

- **1 thread** = processes 1 Y row (or 1 cell)
- Thousands of rows → **saturate the GPU**

## Execution Model



## B200 vs EPYC 9965

	GPU B200	CPU EPYC 9965
Bandwidth	<b>8 TB/s</b>	576 GB/s
FP32	<b>90 TFlops</b>	14 TFlops

GPU: **14× more bandwidth** than CPU → ideal for large sparse meshes

# Kokkos — Performance Portability

## The Problem

- CUDA = NVIDIA only
- OpenMP = CPU only (limited GPU)
- HIP = AMD only
- Rewrite for each platform?

## The Solution: Kokkos

```
// 1. COUNT – unknown result size
parallel_for(num_rows, KOKKOS_LAMBDA(int r) {
    counts[r] = count_intervals(r);
});
// 2. SCAN – compute offsets
exclusive_scan(counts, row_ptr);
// 3. FILL – parallel write
parallel_for(num_rows, KOKKOS_LAMBDA(int r) {
    fill_intervals(r, &out[row_ptr[r]]);
});
```

## CUDA vs Kokkos

### Native CUDA

```
double* d_data;
cudaMalloc(&d_data, n*8);

cudaMemcpy(d_data, h_data,
           n*8, HostToDevice);

kernel<<<B,T>>>(d_data, n);

cudaMemcpy(h_data, d_data,
           n*8, DeviceToHost);

cudaFree(d_data);
```

### Kokkos

```
View<double*> data("d", n);
auto h = create_mirror_view(data);

deep_copy(data, h);

parallel_for(n, KOKKOS_LAMBDA(int
i){
    data(i) = compute(i);
});

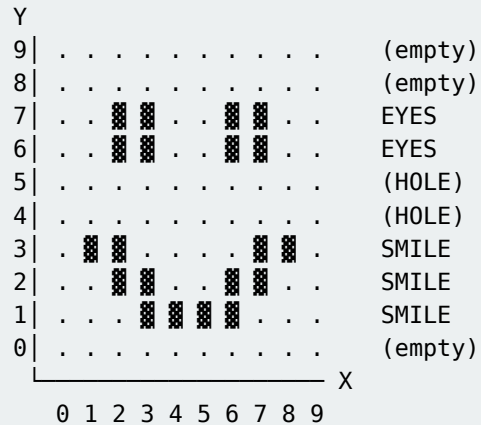
deep_copy(h, data);
// Automatic cleanup (RAII)
```

**Single source code** → compiles for OpenMP, CUDA, HIP, SYCL, Serial

## II. Sparse Representation

# Example: 2D Sparse Mesh with Intervals

## “Smiley” Geometry :-)



## CSR Representation

```
// 5 rows, HOLE Y=4,5  
row_keys = [1, 2, 3, 6, 7] // skips 4,5!  
num_rows = 5
```

```
// Rows with 1 or 2 intervals  
row_ptr = [0, 1, 3, 5, 7, 9]
```

```
intervals = [  
    {3, 7}, // Y=1: smile bottom  
    {2, 4}, {6, 8}, // Y=2: smile thick  
    {1, 3}, {7, 9}, // Y=3: smile corners  
    {2, 4}, {6, 8}, // Y=6: EYES bottom  
    {2, 4}, {6, 8}, // Y=7: EYES top  
]
```

```
num_intervals = 9
```

```
cell_offsets = [0, 4, 6, 8, 10, 12, 14, 16, 18, 20]
```

```
total_cells = 20
```

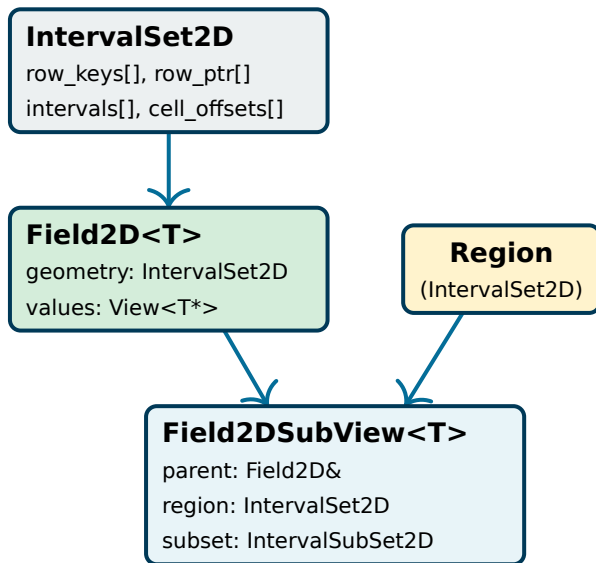
**Hole Y=4,5:** row\_keys jumps from 3 to 6



# III. Data Structures

# Overview — Device Structures

## Core Types



## IntervalSubSet2D

```
struct IntervalSubSet2D {
    IntervalSet2D parent;    // ref
    interval_indices[];      // which intervals
    x_begin[], x_end[];      // restricted range
    row_indices[];           // Y coords
};
```

## SubView: Lazy Intersection

```
// Region = any IntervalSet2D
IntervalSet2DDevice left_bc = make_box_device({0,2,0,ny});
Field2DSubViewDevice<T> sub = make_subview(field, left_bc);

// First op: computes field.geo n region
fill_subview_device(sub, T_inlet, &ctx);

// Time loop: reuses cached intersection
for (int step = 0; step < nsteps; ++step) {
    fill_subview_device(sub, T_inlet); // fast
}
```

## SubView Operations

- `fill_subview_device(sub, val)`
- `scale_subview_device(sub, alpha)`
- `copy_subview_device(dst, src)`
- `apply_stencil_on_subview_device(...)`

**Lazy:** intersection computed on first use

**Cached:** reused for subsequent operations

# IntervalSet2D — Complete CSR Structure

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## C++ Definition

```
template<class MemorySpace>
struct IntervalSet2D {
    // Y coordinates of non-empty rows
    View<RowKey2D*> row_keys; // [num_rows]

    // Index into intervals[] for each row
    View<size_t*> row_ptr;    // [num_rows + 1]

    // All intervals (contiguous)
    View<Interval*> intervals; // [num_intervals]

    // Linear cell offsets
    View<size_t*> cell_offsets; // [num_intervals]

    size_t total_cells;
    int num_rows;
    int num_intervals;
};
```

## Invariants

- row\_keys sorted by increasing Y
- Intervals sorted by X within each row
- No overlap between intervals
- row\_ptr[r+1] - row\_ptr[r] = nb intervals row r

**Template MemorySpace:** Device or Host


# Field2D — Field on Sparse Geometry

## Definition

Associates a **value** with each sparse cell

```
template<class T, class MemorySpace>
struct Field2D {
    IntervalSet2D geometry; // Geometry ref
    View<T*> values;        // [total_cells]
};
```

## Memory Layout

Geometry:	
values[]:	[v0 v1   v2 v3   v4 v5 v6]
	↑        ↑        ↑
offsets:	0        2        4

**Contiguous** values → cache-friendly

## Cell Access

```
// 0(1) - when interval index known
T val = field.at(interval_idx, x);

// 0(log R + log I) - by coordinates
// (binary search on Y, then X)
bool ok = accessor.try_get(x, y, val);
```

## Usage

```
Field2DDevice<double> rho(fluid_geo);
fill_field_device(rho, 1.0);
auto rho_host = to_host(rho); // I/O
```

# SubSet — Targeted Region Operations

## Structure

```
struct IntervalSubSet2D {  
    IntervalSet2D parent; // ref to Field geo  
    interval_indices[]; // which intervals  
    x_begin[], x_end[]; // restricted range  
    row_indices[]; // Y row in parent  
    num_entries;  
};
```

## Usage

```
// Build subset (intersection)  
build_interval_subset(  
    field.geometry, mask, subset, &ctx);  
  
// Operations on subset only  
fill_on_subset(field, subset, 0.0);  
  
// Iteration: O(1) access per entry  
for (e = 0; e < num_entries; ++e) {  
    int iv = interval_indices[e];  
    for (x = x_begin[e]; x < x_end[e]; ++x)  
        field.at(iv, x) = ...; // O(1)  
}
```

## 1D Example: Intersection

Parent:	[==A==]	[==B==]	[==C==]
idx:	0	1	2
	0 8 12	18 22	30
Mask:	[=====M=====]		
	5		25
SubSet:	[=]	[==B==]	[=]
	5 8 12	18 22 25	
entry:	↑	↑	↑
	0	1	2

## SubSet = references to Parent

entry	interval_idx	x_begin	x_end
0	0 (A)	5	8
1	1 (B)	12	18
2	2 (C)	22	25

**No data copy** — just indices + bounds

# Field2DSubView — View on Field + Region

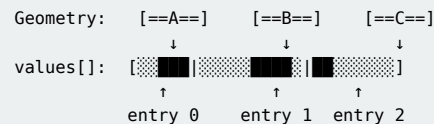
## Structure

```
struct Field2DSubView<T> {  
    Field2D<T> parent;      // ref to field  
    IntervalSet2D region;    // where to operate  
    IntervalSubSet2D subset; // lazy intersection  
};
```

## Lazy Pattern

```
// 1. Create (no computation)  
auto sub = make_subview(field, region);  
// sub.subset is empty  
  
// 2. First op with ctx → triggers build  
fill_subview_device(sub, 0.0, &ctx);  
// sub.subset = field.geo n region  
  
// 3. Next ops reuse cached subset  
scale_subview_device(sub, 2.0); // fast!  
fill_subview_device(sub, 1.0);  // fast!
```

## Memory Mapping



▤ = skipped    ■ = accessed by SubSet

## Access Formula

`values[ offset[idx] + (x - interval.begin) ]`

**O(1)** per cell — no coordinate lookup

# Workspace & AMR Support

## UnifiedCsrWorkspace

Pool of reusable buffers

```
struct UnifiedCsrWorkspace {
    View<int*> int_bufs_[5];
    View<size_t*> size_t_bufs_[2];
    View<RowKey2D*> row_key_bufs_[2];
    View<Interval*> interval_buf_0;

    auto get_int_buf(int id, size_t n) {
        if (n > int_bufs_[id].extent(0))
            Kokkos::resize(int_bufs_[id], n*1.5);
        return subview(int_bufs_[id], {0,n});
    }
};
```

**Avoids** repeated GPU allocations  
Crucial for chained operations

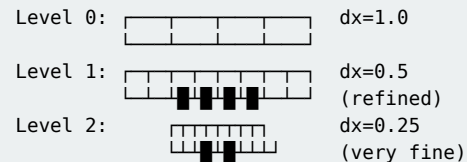
**Note:** Outputs must be pre-allocated  
Use `allocate_interval_set_device()`

## MultilevelGeo (AMR)

Multi-resolution grids

```
template<class MemorySpace>
struct MultilevelGeo {
    double origin_x, origin_y;
    double root_dx, root_dy;
    int num_active_levels;
    Array<GeoView, 16> levels;

    double dx_at(int level) {
        return root_dx / (1 << level);
    }
};
```



# IV. Algorithms



# Binary Search — $O(\log n)$ Lookups Everywhere

## CSR Requires Sorted Data

All lookups rely on binary search:

### 1. Find row by Y coordinate

```
int find_row_by_y(row_keys, num_rows, y) {  
    // Binary search in row_keys[]  
    return lower_bound(row_keys, y);  
}
```

$O(\log R)$  —  $R$  = number of rows

### 2. Find interval by X coordinate

```
int find_interval_by_x(intervals, begin, end, x) {  
    // Binary search in intervals[begin..end]  
    return lower_bound(intervals, x);  
}
```

$O(\log I_{\text{row}})$  —  $I$  = intervals in row

## Combined: Cell Lookup

```
bool try_get(Coord x, Coord y, T& out) {  
    // Step 1: find row  
    int row = find_row_by_y(row_keys, y);  
    if (row < 0) return false;  
  
    // Step 2: find interval in row  
    int iv = find_interval_by_x(  
        intervals, row_ptr[row], row_ptr[row+1], x);  
    if (iv < 0) return false;  
  
    // Step 3: compute offset  
    out = values[offsets[iv] + (x - intervals[iv].begin)];  
    return true;  
}
```

Total:  $O(\log R + \log I)$

**Invariant:** Data must stay sorted!  
(enforced by construction)

# Set Algebra — Binary Operations

## CsrSetAlgebraContext

```
struct CsrSetAlgebraContext {
    UnifiedCsrWorkspace workspace;
    // Pool of reusable GPU buffers:
    // - int_bufs_[5], size_t_bufs_[2]
    // - row_key_bufs_[2], interval_buf_
    // Auto-grows on demand, never shrinks
};
```



Same ctx reused → **zero allocations** after warmup

## Complete Example

```
CsrSetAlgebraContext ctx; // create once

auto domain = make_box_device({0,400,0,160});
auto obstacle = make_disk_device({80,80,20});

auto fluid = allocate_interval_set_device(
    domain.num_rows,
    domain.num_intervals + obstacle.num_intervals);

set_difference_device(domain, obstacle, fluid, ctx);
```

## Chaining with Buffer Reuse

```
CsrSetAlgebraContext ctx;

// Pre-allocate output buffers ONCE
auto set1 = allocate_interval_set_device(512, 2048);
auto set2 = allocate_interval_set_device(512, 2048);

// Compute: set1 = A ∪ B
set_union_device(A, B, set1, ctx);

// Compute: set2 = set1 \ C
set_difference_device(set1, C, set2, ctx);

// ... use set2 (e.g., create Field2D on it) ...

// Later: reuse same buffers!
set_intersection_device(D, E, set1, ctx); // set1 reused
set_union_device(set1, F, set2, ctx);    // set2 reused
```

**Allocate once** → reuse for entire simulation  
**ctx + set1 + set2:** zero GPU malloc in hot loop

# Row Mapping — Why and How

## GPU Constraint

1 thread = 1 output row

We need to know output rows **before** parallel processing.

## Which Rows Participate?

A: 2 5 8

B: 3 5 8 9

Op	Output rows	Count
$A \cap B$	{5, 8}	2
$A \cup B$	{2, 3, 5, 8, 9}	5
$A \setminus B$	{2}	1

## Row Mapping per Operation

**Intersection** — rows in both A and B

```
// Binary search A rows in B
map[i] = binary_search(B.row_keys, A.row_keys[i]);
// Keep only matched rows (map[i] >= 0)
```

**Union** — rows in A or B (merge sorted)

```
// 1. Search A-B and B-A
// 2. Flag-Scan-Compact: extract B-only rows
// 3. Interleave A + B-only maintaining order
```

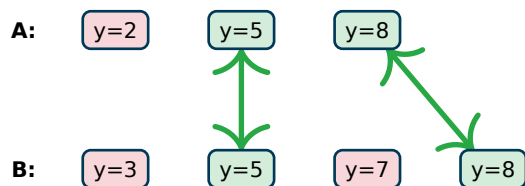
**Difference** — rows in A (check B for each)

```
// Output = A.row_keys (same structure)
// map[i] = search A.row_keys[i] in B
// If found: must subtract intervals
```

**Result:** output row list + per-row mapping  
→ enables `parallel_for(num_output_rows, ...)`

# Intersection — How It Works

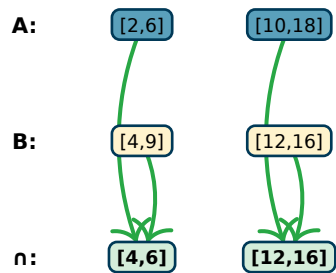
## Phase 1: Row Mapping



Binary search:  $O(\log n)$  per row

## Phase 2: Interval Merge (per row)

Row  $y=5$  — 2 intervals each



$O(n+m)$  sweep —  $\max(\text{begin}), \min(\text{end})$

## GPU Pattern: Count-Scan-Fill

**Why?** GPU threads can't dynamically allocate — output size must be known before parallel write.



**1. COUNT** — how many intervals per row?

```
row_counts[i] = count_intersect(A[i], B[i])
```

Parallel per row — don't write yet

**2. SCAN** — where does each row start?

```
row_ptr = exclusive_scan(row_counts)
```

Prefix sum  $\rightarrow$   $\text{row\_ptr}[i]$  = write offset

**3. FILL** — write results at known offsets

```
fill_intersect(A[i], B[i], out, row_ptr[i])
```

Parallel per row — no conflicts!

Same pattern for  $\cup$ ,  $\cap$ ,  $\oplus$

# Stencil Access — Sparse Geometry

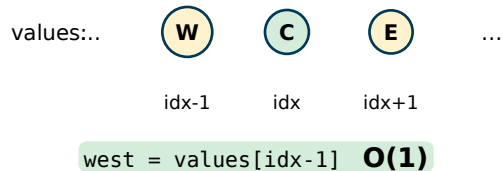
## The Problem

On dense grid: `north = values[i + nx]`

On sparse CSR: row `y+1` may not exist, or have different intervals!

## Horizontal: Easy

Same interval → contiguous in memory

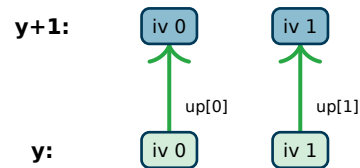


## Vertical: Pre-computed Mapping

```
struct VerticalIntervalMapping {  
    View<int*> up_interval;  
    View<int*> down_interval;  
};
```

Built once, maps each interval to its neighbor in  $y \pm 1$

## Vertical Mapping Diagram



Condition: same interval count per row

## Access North

```
int up_idx = up_interval[center_idx];  
Interval iv = intervals[up_idx];  
size_t off = offsets[up_idx] + (x - iv.begin);  
return values[off]; // O(1)
```

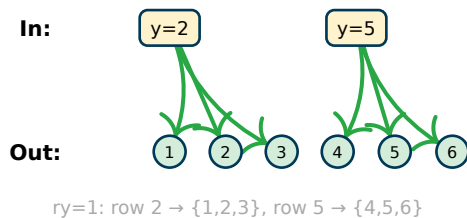
## User Interface

```
// Stencil functor receives:  
CsrStencilPoint<T> p;  
p.center(); p.west(); p.east();  
p.north(); p.south(); // All O(1)
```

# Expand (Dilation) — How It Works

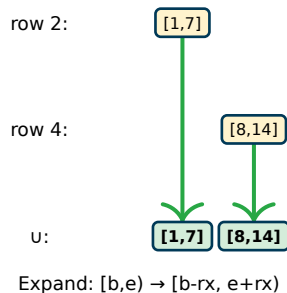
## Phase 1: Row Mapping

Input row  $y \rightarrow$  output rows  $[y-ry, y+ry]$



## Phase 2: N-way Union (per row)

Output row  $y=3$  — inputs: rows 2,3,4



## Interval Expansion

Original:

[4,8]

$rx=2$ :

[2,10]

$[begin-rx, end+rx)$

## GPU Pattern: Count $\rightarrow$ Scan $\rightarrow$ Fill

### 1. COUNT — N-way union count

```
row_counts[i] = n_way_union_count(
    rows[map_start[i]..map_end[i]], rx);
```

### 2. SCAN

```
row_ptr = exclusive_scan(row_counts);
```

### 3. FILL — N-way union write

```
n_way_union_fill(
    rows[map_start[i]..map_end[i]], rx,
    out, row_ptr[i]);
```

**Shrink:** N-way  $n$ ,  $[b+rx, e-rx)$

# AMR — Restrict & Prolong

## Coordinate Mapping (2:1)



## Restrict (Fine → Coarse)

```
coarse[x,y] = 0.25 * (
    fine[2x,  2y ] + fine[2x+1, 2y ] +
    fine[2x,  2y+1] + fine[2x+1, 2y+1]
);
```

Average of 4 fine cells → 1 coarse cell

## Floor/Ceil for Negative Coords

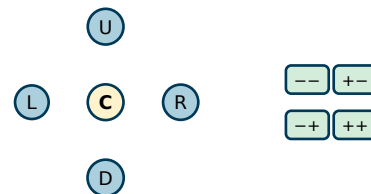
```
// Handles negative coordinates correctly
floor_div2(x) = (x>=0) ? x/2 : (x-1)/2;
ceil_div2(x)  = (x>=0) ? (x+1)/2 : x/2;
// Example: floor_div2(-3) = -2, not -1
```

## Prolong (Coarse → Fine)

### 1. Injection (simple copy)

```
fine[x,y] = coarse[x/2, y/2];
```

### 2. Linear Prediction (with gradients)



```
grad_x = 0.125 * (R - L);
grad_y = 0.125 * (U - D);
sign_x = (x%2==0) ? -1 : +1;
sign_y = (y%2==0) ? -1 : +1;
fine = C + sign_x*grad_x + sign_y*grad_y;
```

**O(1)** per cell with pre-computed mapping

# Field Operations

## Basic Operations

```
// Algebra & reductions
field_add_device(a, b, result);
T dot = field_dot_device(a, b);

// 5-point stencil (W, C, E, S, N)
apply_csr_stencil_on_set_device(
    dst, src, region,
    KOKKOS_LAMBDA(CsrStencilPoint p) {
        return 0.25 * (p.west + p.east
                      + p.south + p.north);
    });
```

## AMR: Restrict & Prolong

```
// Fine → Coarse (average 4 cells)
restrict_field_device(fine, coarse);

// Coarse → Fine (interpolation)
prolong_field_device(coarse, fine);
```

## Threshold: Field → Geometry

```
// Select cells where |value| > epsilon
IntervalSet2DDevice active =
    threshold_field(field, epsilon);
// Use case: detect shock, refine there
```

## Remap: Change Geometry

```
// Project src onto dst geometry
// (overlap → copy, else → default)
remap_field_device(src, dst, default_val);
```

src geo: 

dst geo: 

result: 

copy ↑    ↑ default



# Mathematical Morphology & AMR

## Dilation / Erosion

```
// N-way union with ±radius offset
row_n_way_union_impl(rows[], radius, out)

// N-way intersection with shrink
row_n_way_intersection_impl(rows[], r, out)
```

Original:   
Dilate(1):  (+1 sides)  
Erode(1):  (-1 sides)







## 2D Extension

- Consider rows  $y-r$  to  $y+r$
- Merge with N-way operation
- Implicit structuring element (square)

## AMR Operations

```
// Coarsening: fine → coarse
build_row_coarsen_mapping(fine, ws)
// y_coarse = y_fine / 2, merge X

// Refinement: coarse → fine
refine_level_up_device(coarse, ws)
// [a,b) → [2a, 2b), double Y
```

Fine (level 1):  
Y=3:   
Y=2:   
Y=1:   
Y=0:   
→  
Coarse (level 0):  
Y=1:  (merge Y=2,3)  
Y=0:  (merge Y=0,1)

## Field Transfer

```
// Projection fine → coarse (average)
// Prolongation coarse → fine (interp)
build_amr_interval_mapping(coarse, fine)
```

# V. Demo

# Mach2 Cylinder — Multi-Level AMR Simulation

## Description

2D compressible flow simulation:

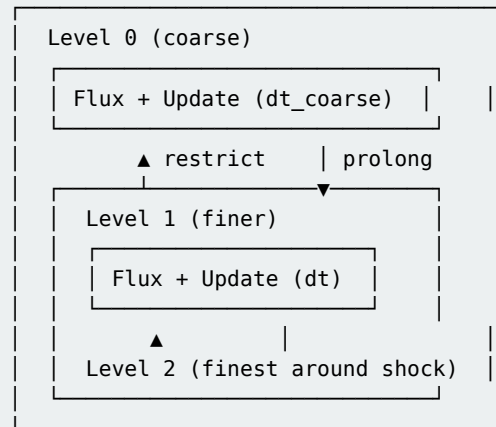
- **Mach 2** supersonic around a cylinder
- 1st order Godunov scheme + Rusanov flux
- **Dynamic AMR**: 4 levels

## Subsetix Usage

```
// Fluid geometry = domain - obstacle
auto fluid = set_difference_device(
    make_box_device(domain),
    make_disk_device(cylinder),
    ctx);

// Conserved fields (ρ, pu, pv, E)
Field2DDevice<Real> rho(fluid);
Field2DDevice<Real> rhou(fluid);
// ...
```

## AMR Architecture



## Dynamic Refinement

- Indicator: density gradient
- `expand_device()` for guard zones
- Remeshing every N time steps

# Mach2 Cylinder — Results & Visualization

---

## Generated Outputs

```
mach2_cylinder/
├─ fluid_geometry.vtk
├─ obstacle_geometry.vtk
├─ refine_mask_lvl{1,2,3}.vtk
├─ fine_geometry_lvl{1,2,3}.vtk
├─ step_00001_density.vtk
├─ step_00001_l0_density.vtk
├─ step_00001_l1_density.vtk
├─ step_00001_mach.vtk
├─ step_00001_pressure.vtk
└─ ...
```

## Execution Command

```
./mach2_cylinder \
--nx 400 --ny 160 \
--radius 20 \
--mach-inlet 2.0 \
--max-steps 5000 \
--output-stride 50 \
--amr --amr-levels 4
```

## Observed Phenomena

- **Bow shock** in front of the cylinder
- Density/pressure gradient captured
- AMR refinement follows the shock

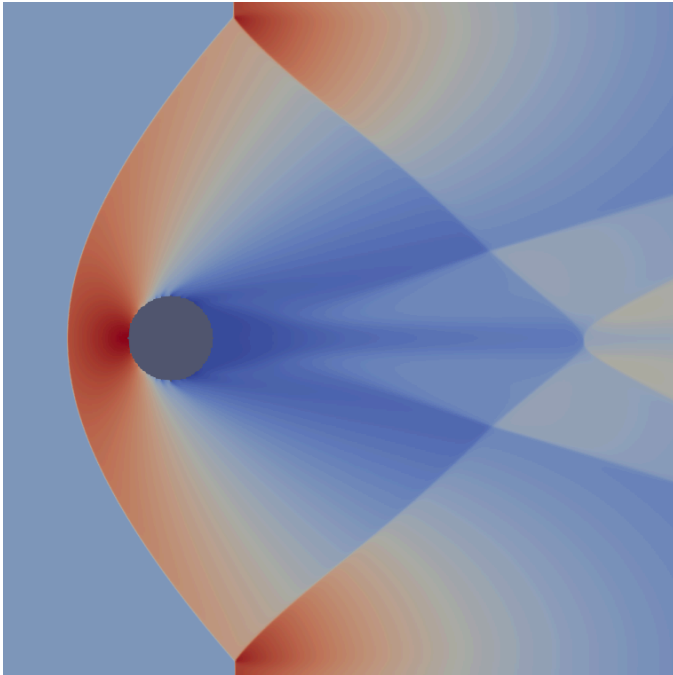
## Key Technical Points

- 1st order Godunov + Rusanov flux
- Struct-of-Arrays: ConservedFields ( $\rho$ ,  $pu$ ,  $pv$ ,  $E$ )
- `threshold_field()` → detect shock gradient
- `expand_device()` → guard cells around refined zone
- `restrict_fine_to_coarse()` / `prolong_guard_from_coarse()`
- `write_multilevel_field_vtk()` for ParaView

**Sparse:** computation only on fluid cells!

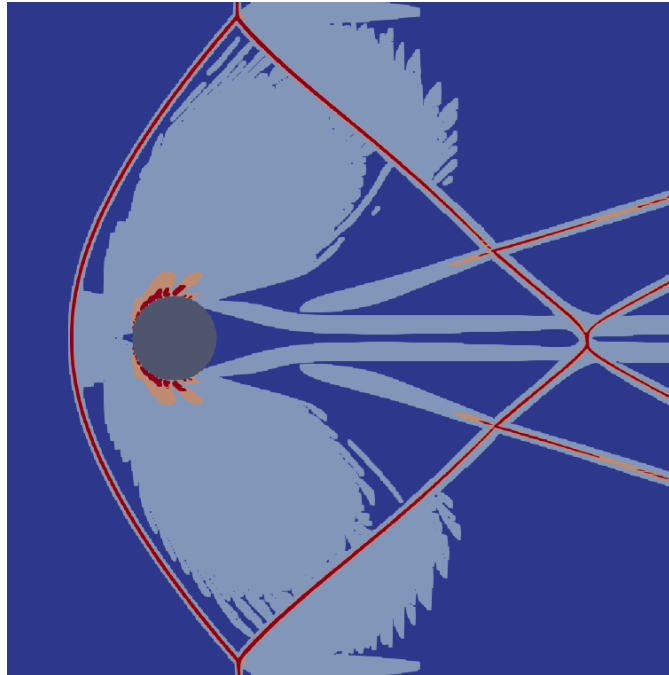
# Mach2 Cylinder — Visual Results

**Density Field**



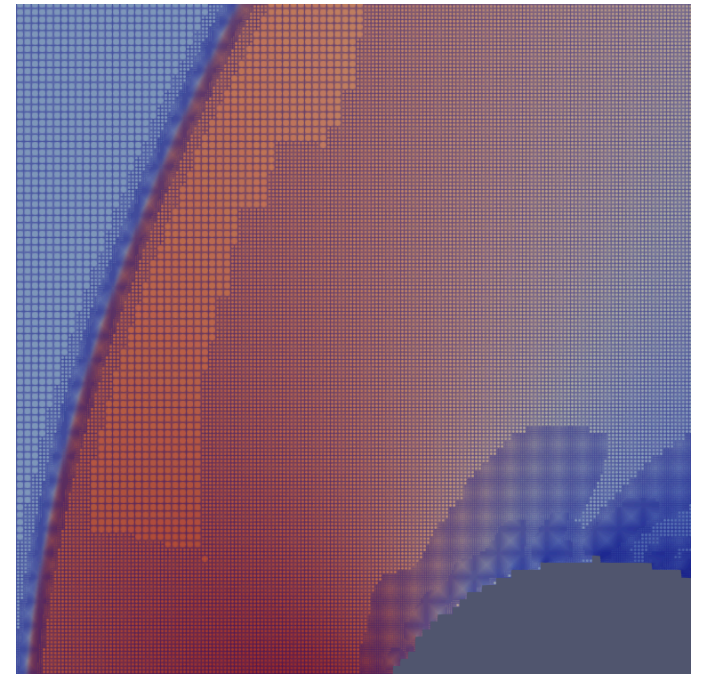
Bow shock in front of cylinder  
Colormap: blue (low) → red (high)

**AMR Levels**



Automatic refinement zones  
near the shock front

**Mesh Zoom**



Multi-level AMR resolution  
near the bow shock

**4 AMR levels** (9-12) — Automatic refinement based on density gradient

# Thank You!

Questions?

## Key Points

- CSR interval representation
- Count-Scan-Fill pattern
- Kokkos parallelism (CPU/GPU)
- Workspace for memory reuse
- Multi-level AMR (Mach2)

## Contact

Sébastien DUBOIS  
HPC@Maths Team

Code: `include/subsetix/`  
Demo: `examples/mach2_cylinder/`

# Appendices

# Appendix A: Project Evolution

## Implementation History

Version	Description	Performance	Status
v1	CPU only, Sparse CSR + Workspaces First sequential implementation	Faster than baseline	✓ Stable
v2	Multithreaded <b>Tiled</b> Sparse CSR OpenMP and TBB backends Tiling for locality	Excellent on large mesh	⚠ Complex Likely bugs
v3	CUDA only GPU set algebra Proof of concept	<b>Fastest</b>	✓ PoC validated
v4	<b>Kokkos</b> (current version) Non-tiled Sparse CSR OpenMP + CUDA portability	Slower than v2/v3	✓✓ <b>Reliable</b> Verified

### Lessons Learned

- **Tiling** improves locality but greatly increases complexity
- Native CUDA faster but less portable
- Kokkos = best **reliability/portability** tradeoff

### Final Choice: Kokkos

- **Single** code for CPU and GPU
- Simplified maintenance
- Easy testing and verification
- Active ecosystem (Sandia, Trilinos)



# Appendix B: Why Kokkos?

---

## Comparison with Native CUDA

Aspect	CUDA	Kokkos
Portability	NVIDIA only	<b>Multi-vendor</b>
Syntax	<<<>>>	<b>C++ standard</b>
Memory	cudaMalloc	<b>View&lt;T*&gt;</b>
CPU Debug	Difficult	<b>Easy (Serial)</b>
Maintenance	Duplicated code	<b>Single code</b>
Performance	<b>Optimal</b>	90-95%

## Supported Backends

- **OpenMP**: CPU multi-thread
- **CUDA**: NVIDIA GPU
- **HIP**: AMD GPU
- **SYCL**: Intel GPU
- **Serial**: debug and tests

## Benefits for This Project

### 1. Faster Development

Debug on CPU (Serial/OpenMP), deploy on GPU

### 2. Reliable Tests

Same code tested on CPU and GPU  
No hidden “GPU-only” bugs

### 3. Std Algorithms

transform, reduce, scan, copy...  
Familiar API, platform-optimized

### 4. Ecosystem

Trilinos, ArborX, Cabana...  
Sandia National Labs support

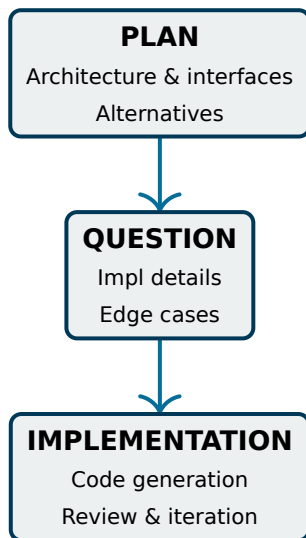
# Appendix C: Development Methodology

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## Models Used

- **Claude 4.5 Opus** (Anthropic)
- **Claude 4.5 Sonnet** (Anthropic)
- **gpt-5.1-codex-max** (OpenAI)

## Work Pattern



## Observed Benefits

- **Rapid exploration** of designs
- Generated inline documentation
- Automatically suggested tests
- Assisted refactoring

## Points of Attention

- Systematic code verification
- LLMs can hallucinate APIs
- Always compile and test
- Maintain **architectural control**

LLM = **accelerator**, not replacement  
Human expertise remains essential