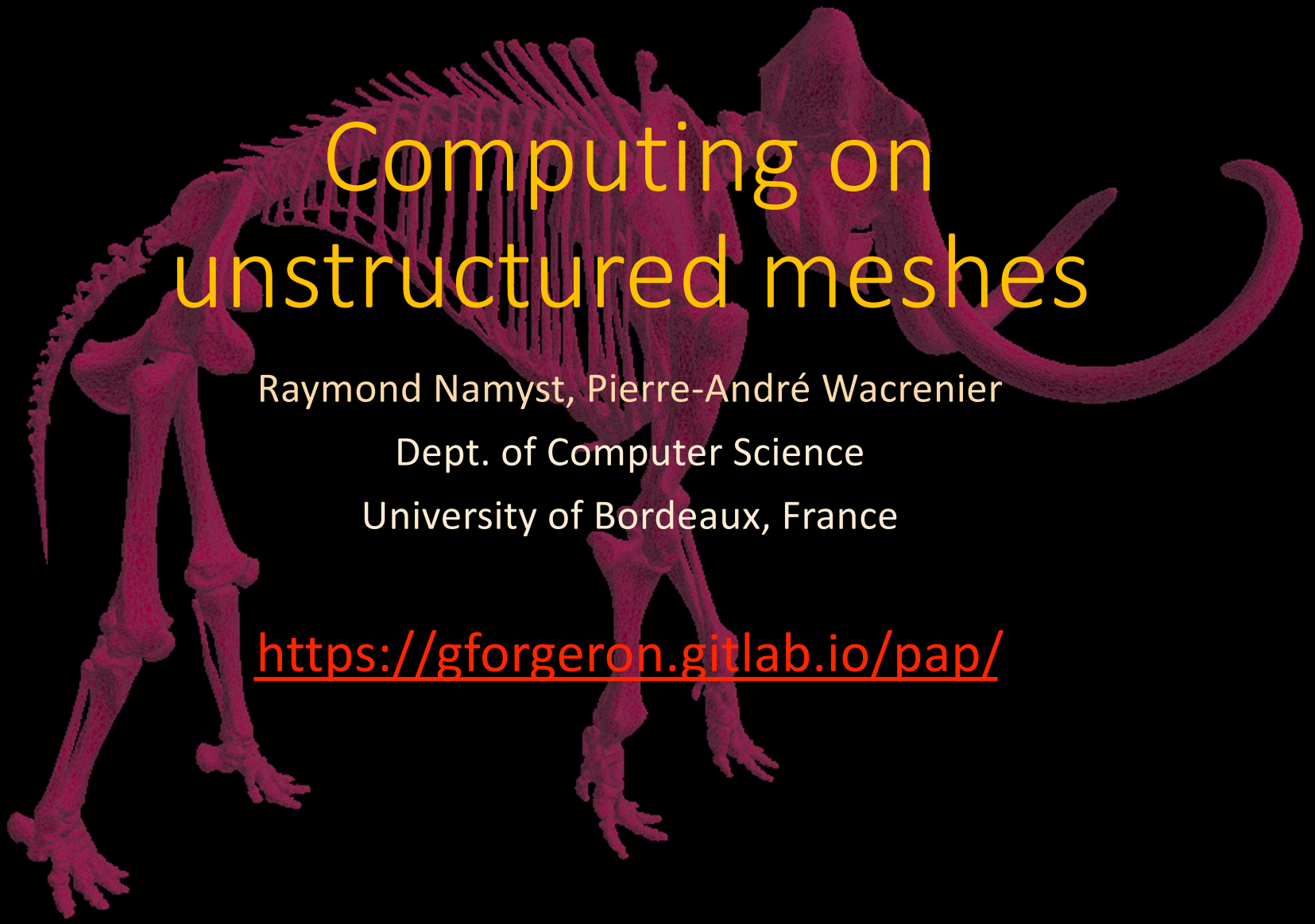

Computing on unstructured meshes

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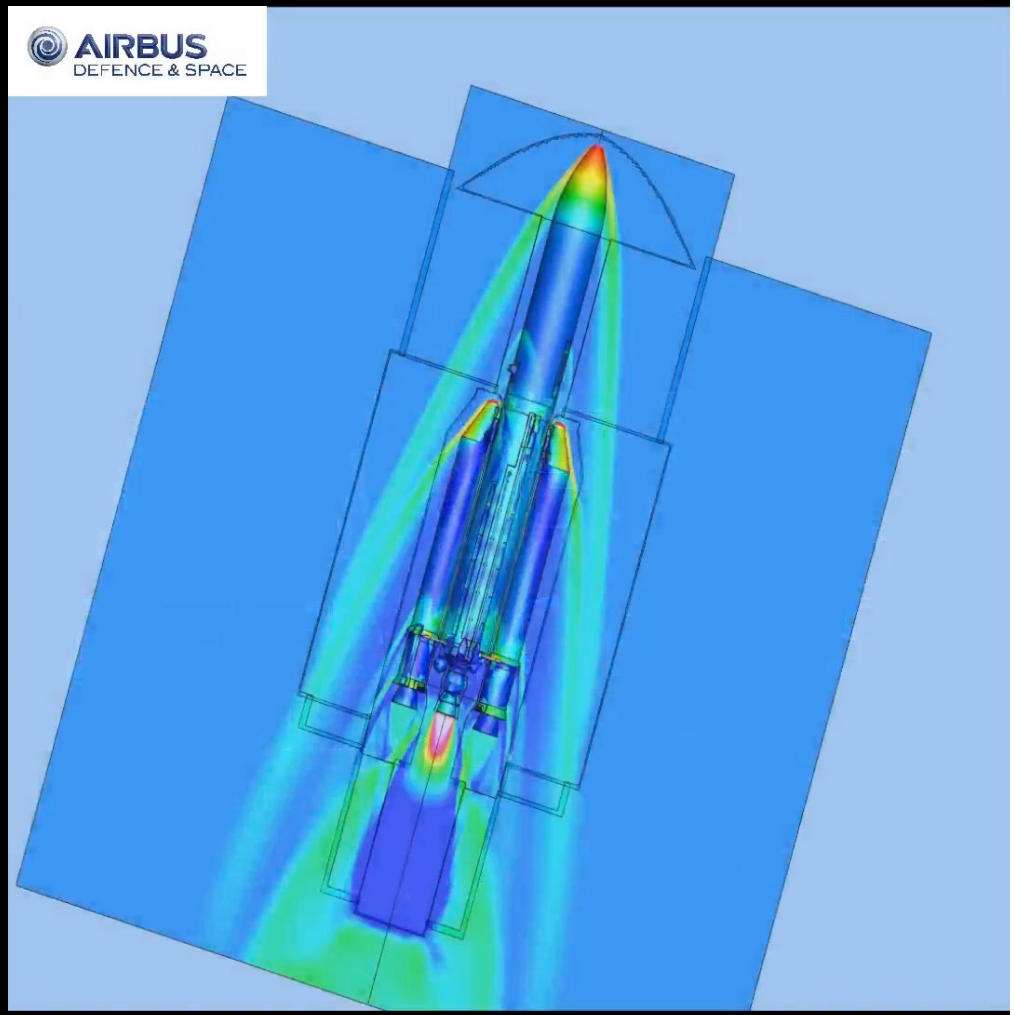
https://gforgeron.gitlab.io/pap/

Numerical simulation

- Provide valuable insights and aiding in the understanding of complex phenomena
  - difficult to analyze using analytical methods or physical experiments
    - blast wave propagation during rocket take-off
    - launch vehicle stage separations
    - noise generated by aircraft propellers
  - E.g. CFD simulations
    - Computational Fluid Dynamics



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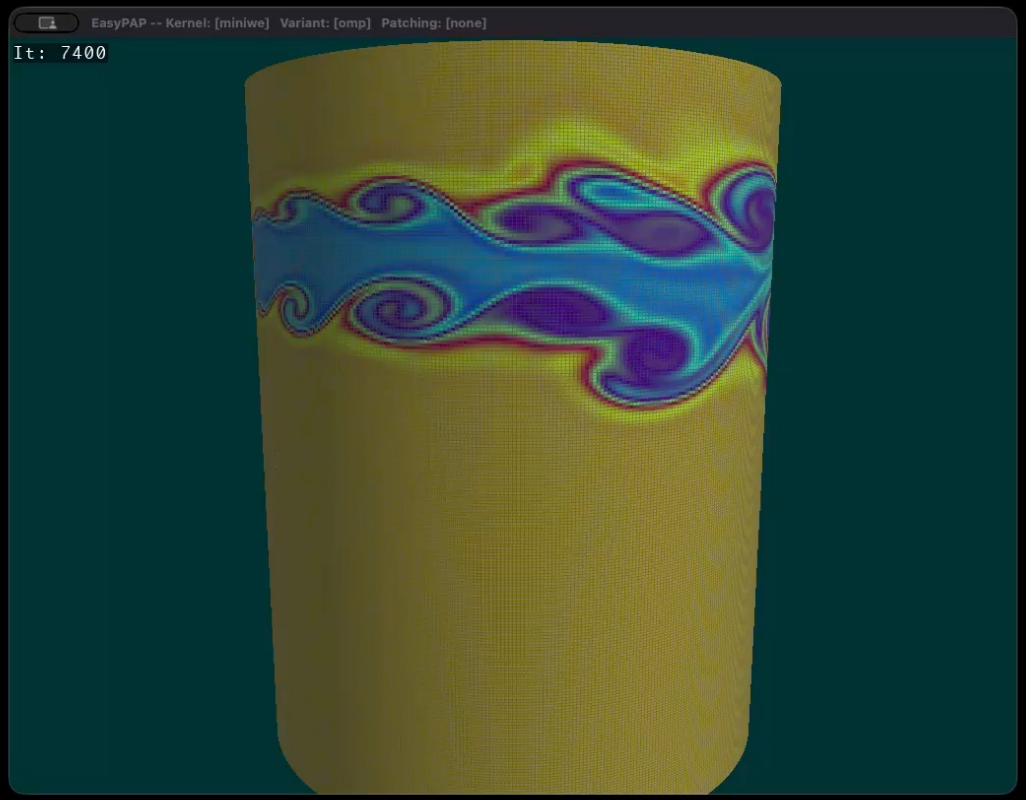
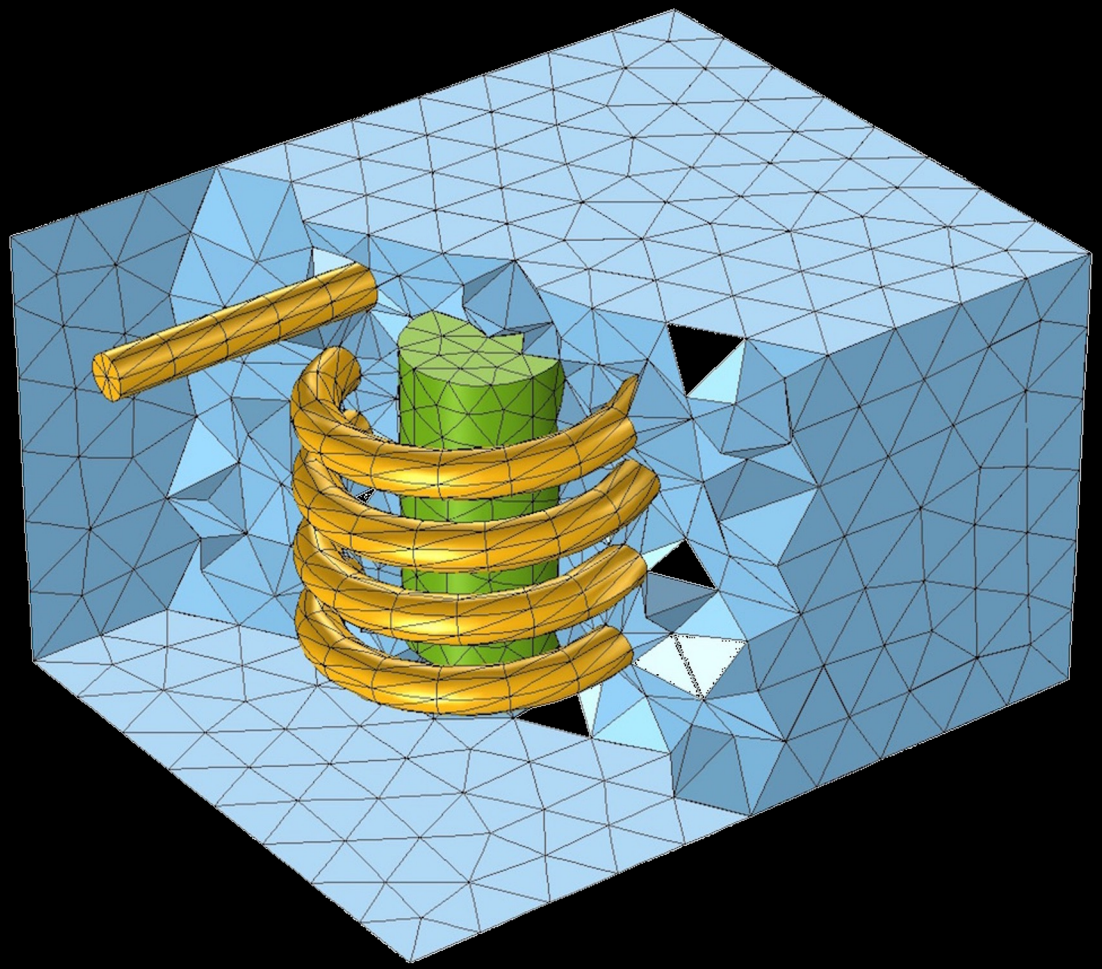
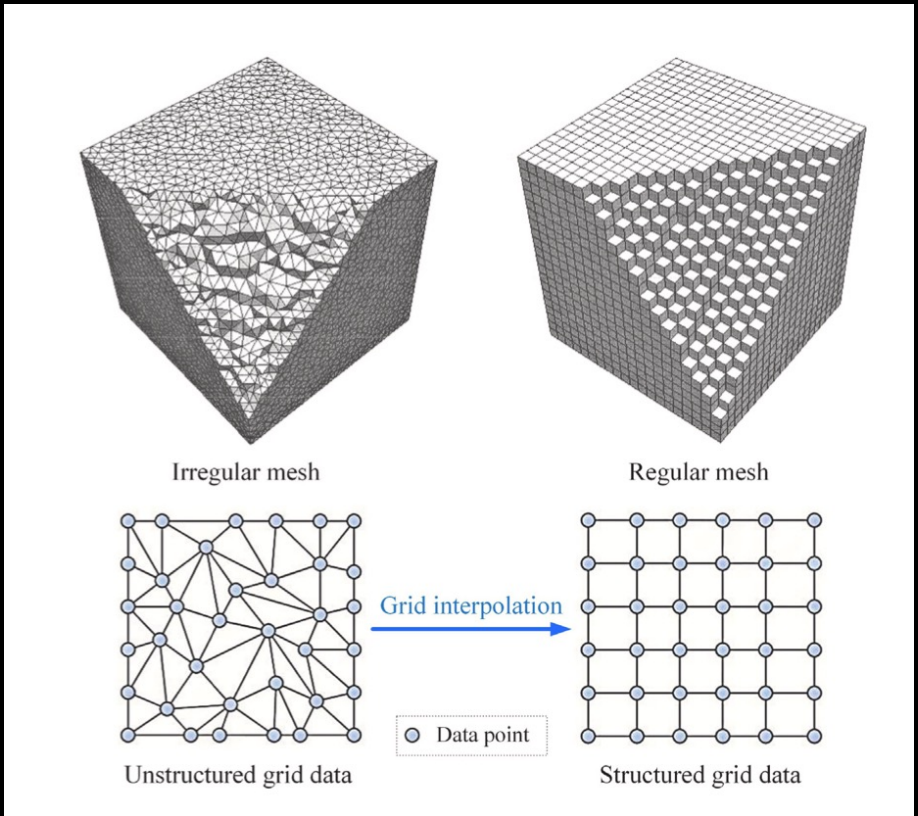
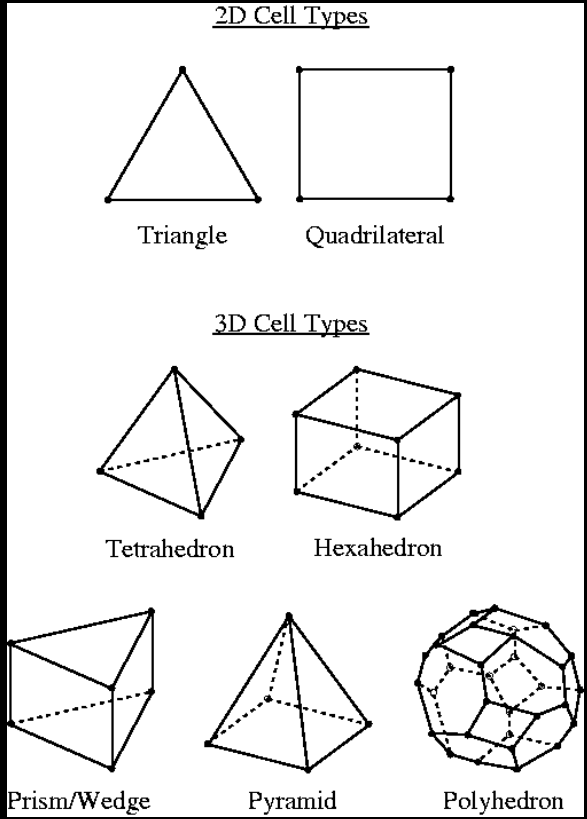


Numerical modeling of phenomena

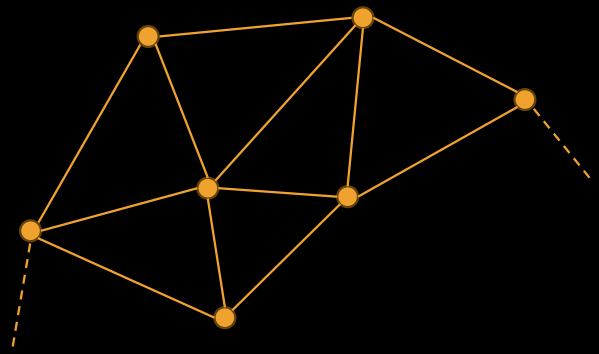


Structured vs unstructured





EasyPAP and Meshes

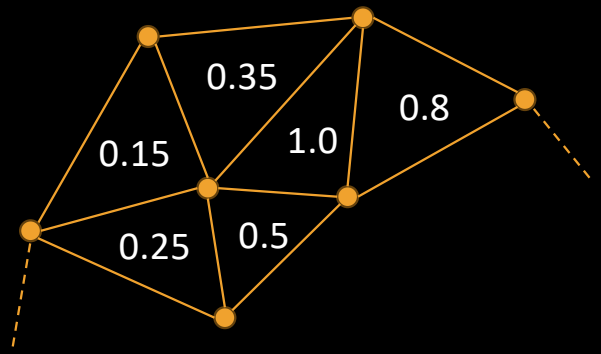


- Meshes come from .OBJ files
  - Straightforward text format
    - Vertices, faces, connectivity
    - [+ default partitioning]

```
v 1.3764 0.76354 0.0236
…
f 0 1 2
f 0 2 3
…
n 1 15 20
n 0 2
…
```

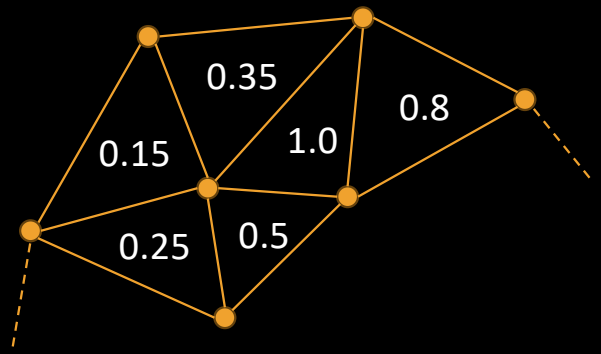
  - Most information is only used for 3D display

Doing computations on unstructured meshes



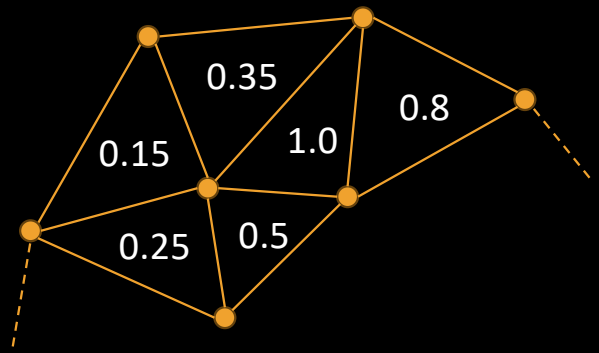
- A value representing a physical quantity (e.g. temperature) is attached to each cell
  - Normalized in [0.0..1.0]

Doing computations on unstructured meshes



- A value representing a physical quantity (e.g. temperature) is attached to each cell
  - Normalized in [0.0..1.0]
- Cells are colored by interpolation using a gradient palette

Visualizing the values



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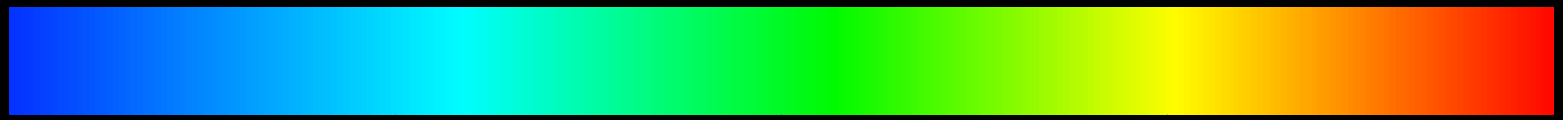
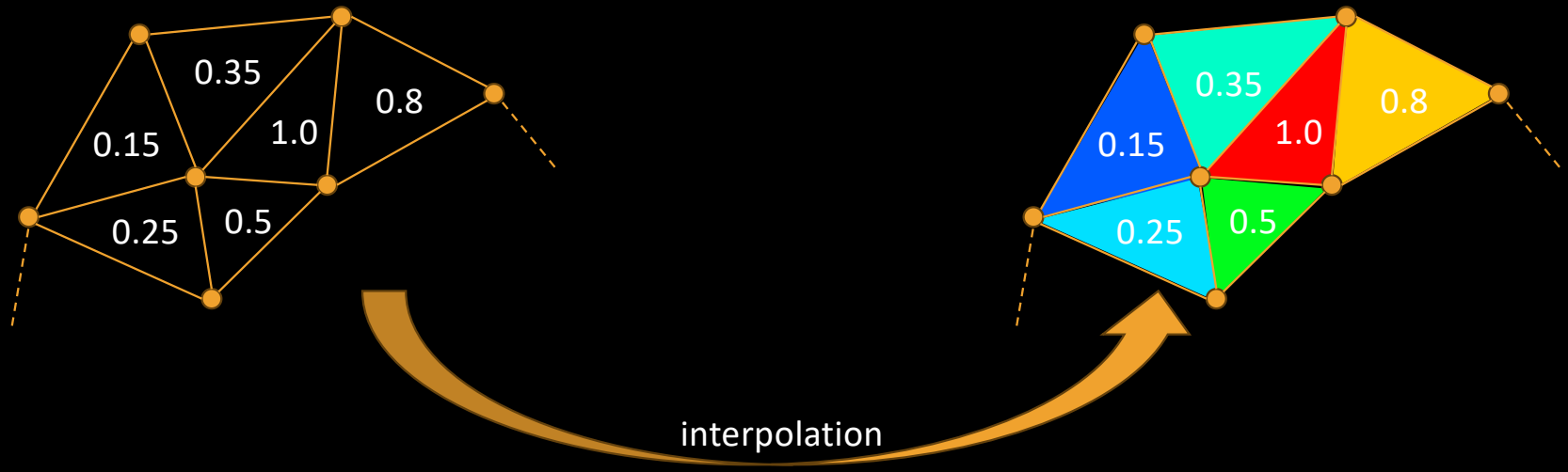
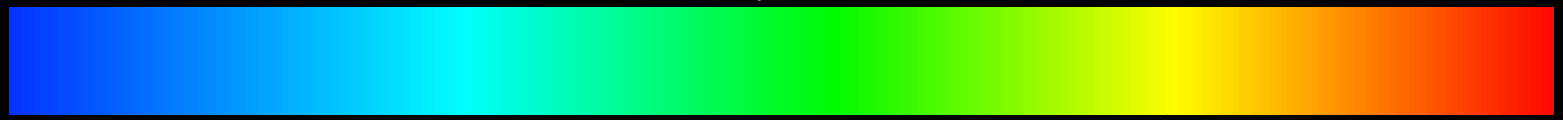


0.0 (blue) 0.25 (cyan) 0.5 (green) 0.75 (yellow) 1.0 (red)

Visualizing the values



color palette



0.0	0.25	0.5	0.75	1.0
(blue)	(cyan)	(green)	(yellow)	(red)

Doing computations on unstructured meshes

- A value representing a physical quantity (e.g. temperature) is attached to each cell
  - Normalized in [0.0..1.0]
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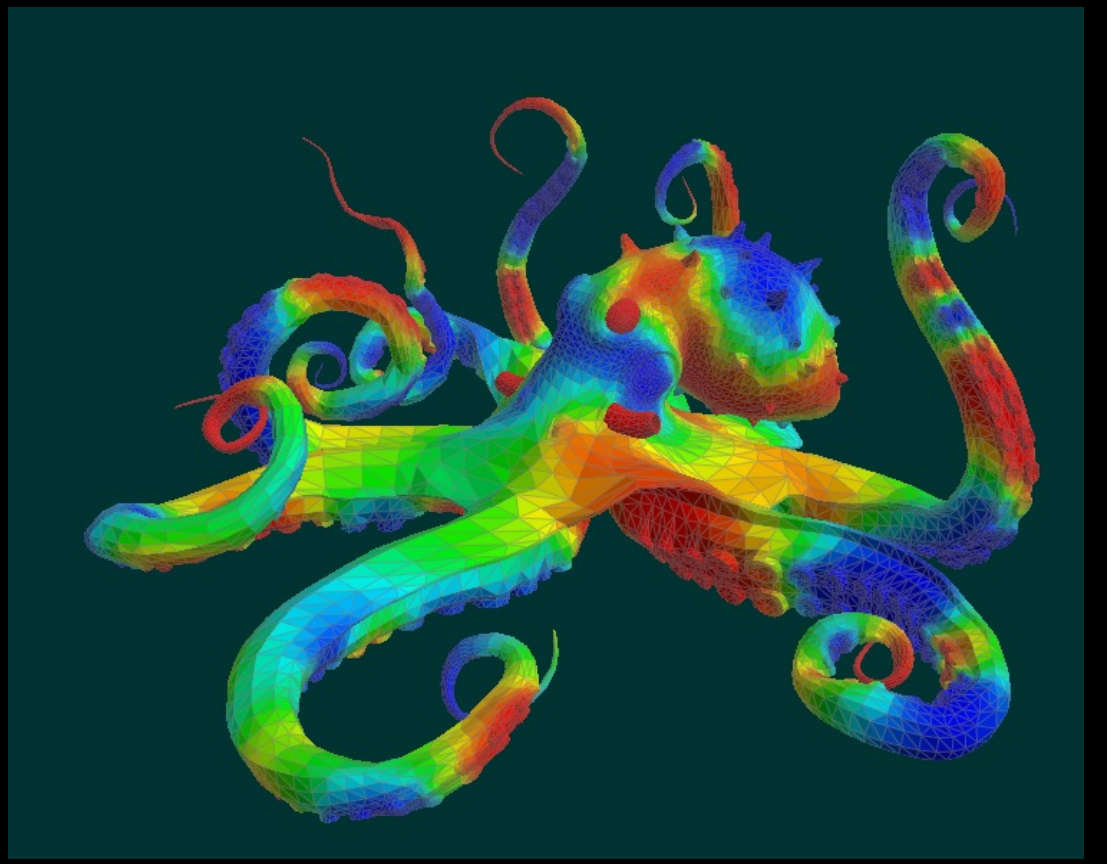
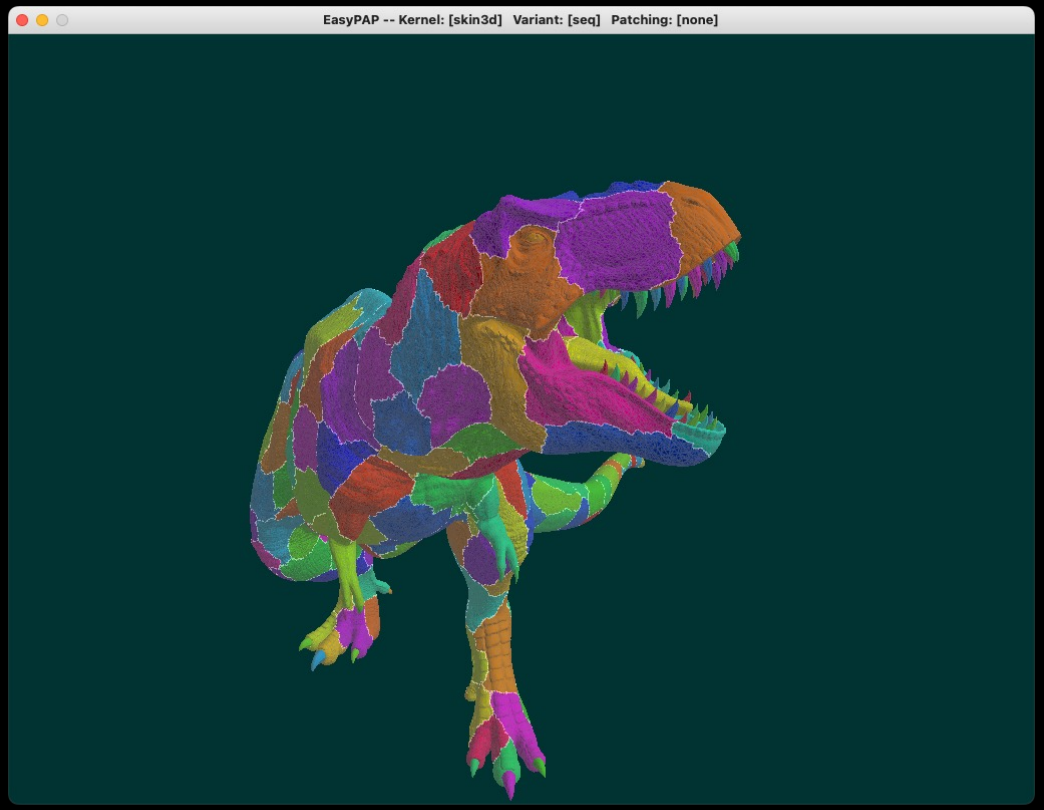


Working with meshes in EasyPAP

- Pixels → Cells
  - Variable number of neighbors
- Colors → float values

- In EasyPAP, the programmer sees
  - NB_CELLS
  - cur_data (cell) and next_data (cell)
    - Arrays of floating-point values
    - Remember: values must be in range 0.0-1.0

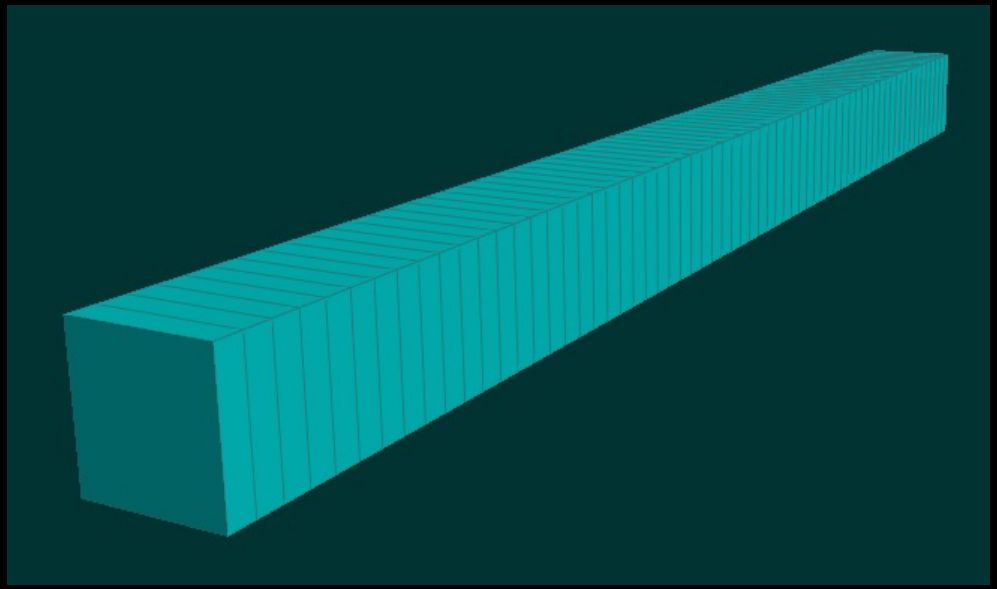


Setting a simple 2-point palette

```
void sample3d_config (char *param)
{
  // Choose color palette
  float colors[] = {0.0f, 0.8f, 0.8f, 1.f,  // cyan
                    0.8f, 0.0f, 0.8f, 1.f}; // pink
  mesh_data_set_palette (colors, 2);
}
```

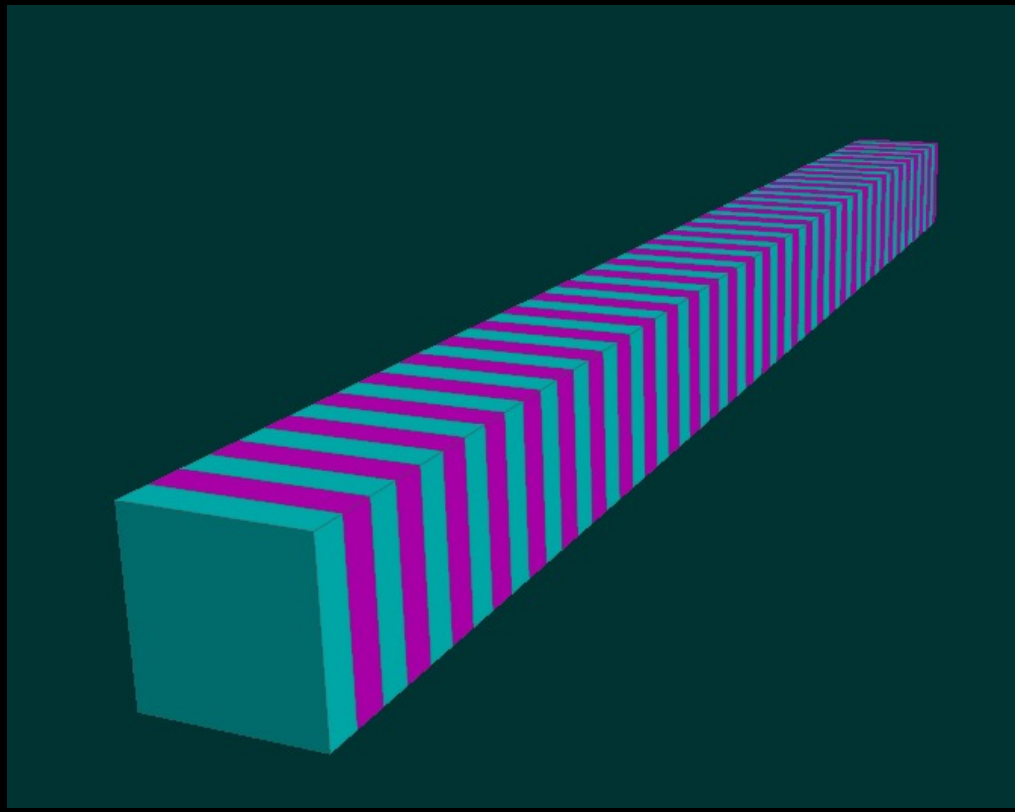
Example

```
///////////////////////////// Sequential version (seq)
// Suggested cmdline:
// ./run -lm <mesh_file> -k sample3d -si
unsigned sample3d_compute_seq (unsigned nb_iter)
{
  for (unsigned it = 1; it <= nb_iter; it++)
    for (int c = 0; c < NB_CELLS; c++)
      cur_data (c) = 0.0;

  // Stop after first iteration
  return 1;
}
```



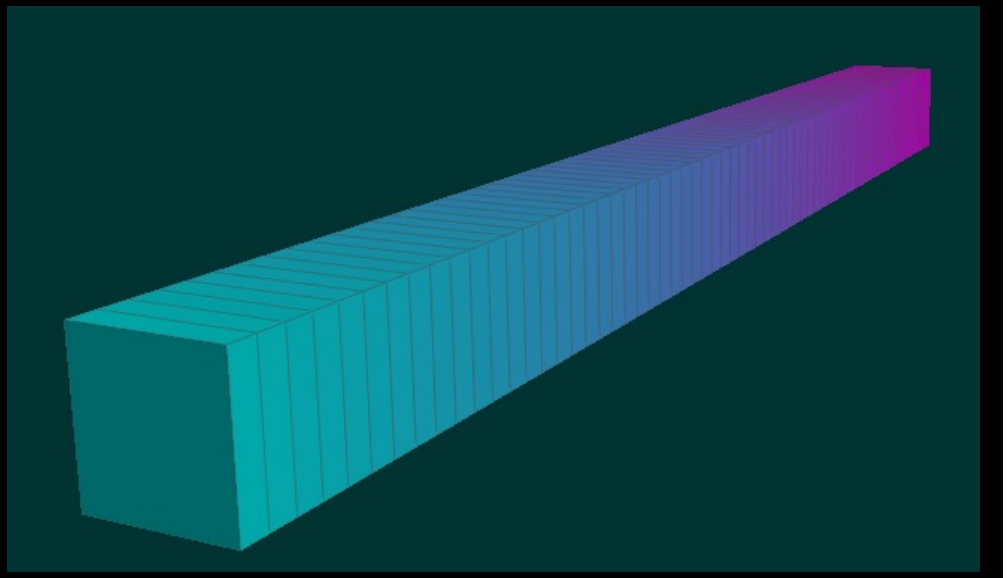
Example alternating 0 and 1

```
///////////////////////////// Sequential version (seq)
// Suggested cmdline:
// ./run -lm <mesh_file> -k sample3d -si
unsigned sample3d_compute_seq (unsigned nb_iter)
{
  for (unsigned it = 1; it <= nb_iter; it++)
    for (int c = 0; c < NB_CELLS; c++)
      cur_data (c) = (float)(c & 1);

  // Stop after first iteration
  return 1;
}
```

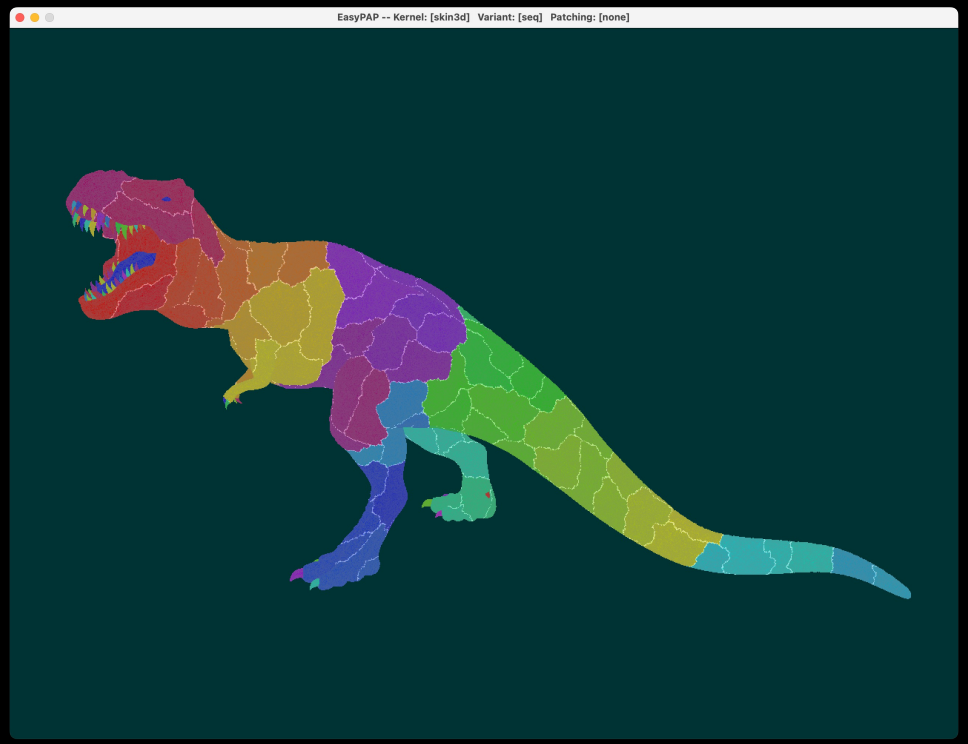


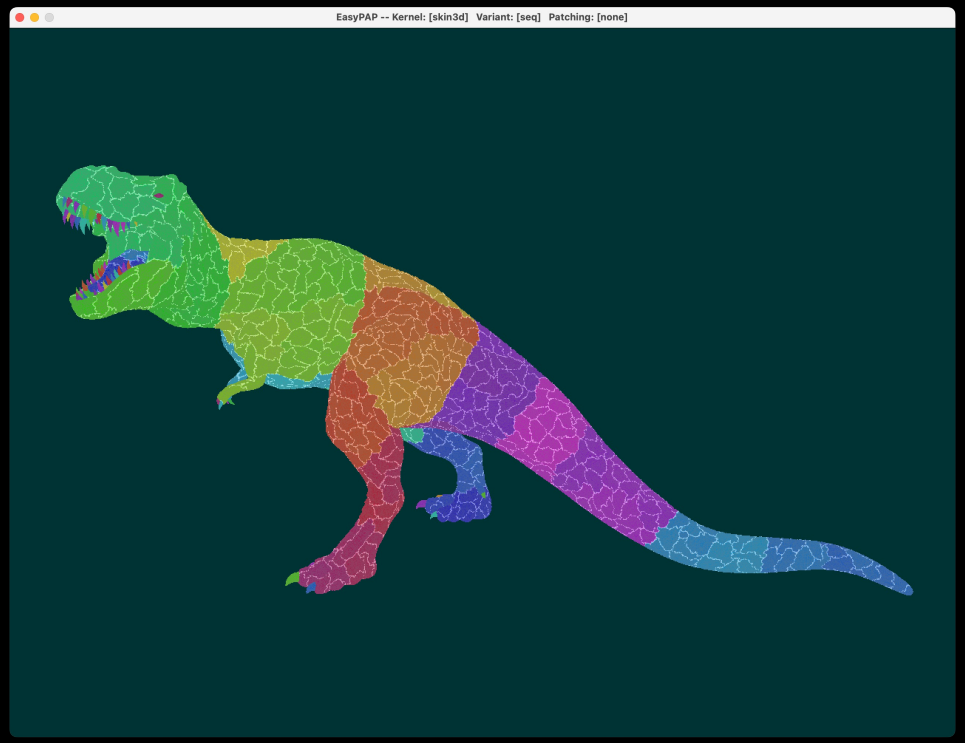
Example using the linear [0..1] spectrum

```
///////////////////////////// Sequential version (seq)
// Suggested cmdline:
// ./run -lm <mesh_file> -k sample3d -si
unsigned sample3d_compute_seq (unsigned nb_iter)
{
  for (unsigned it = 1; it <= nb_iter; it++)
    for (int c = 0; c < NB_CELLS; c++)
      cur_data (c) = c / (float)(NB_CELLS-1) ;

  // Stop after first iteration
  return 1;
}
```



Grouping cells in patches as a mean to control granularity of parallelism

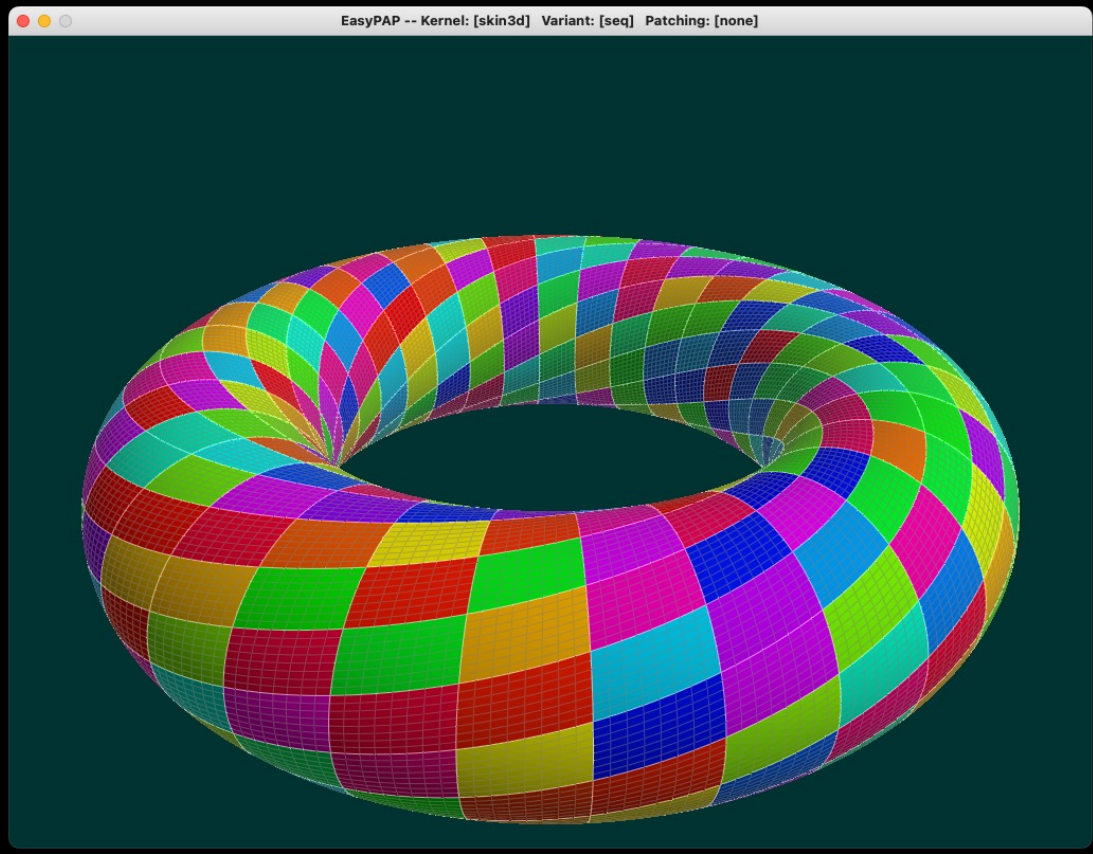




Where are my tiles?

- Pixels → Cells
  - Variable number of neighbors
- Colors → float values

- Tiles → Patches
  - Obtained either by
    - Space filling curves
    - Scotch partitioning library



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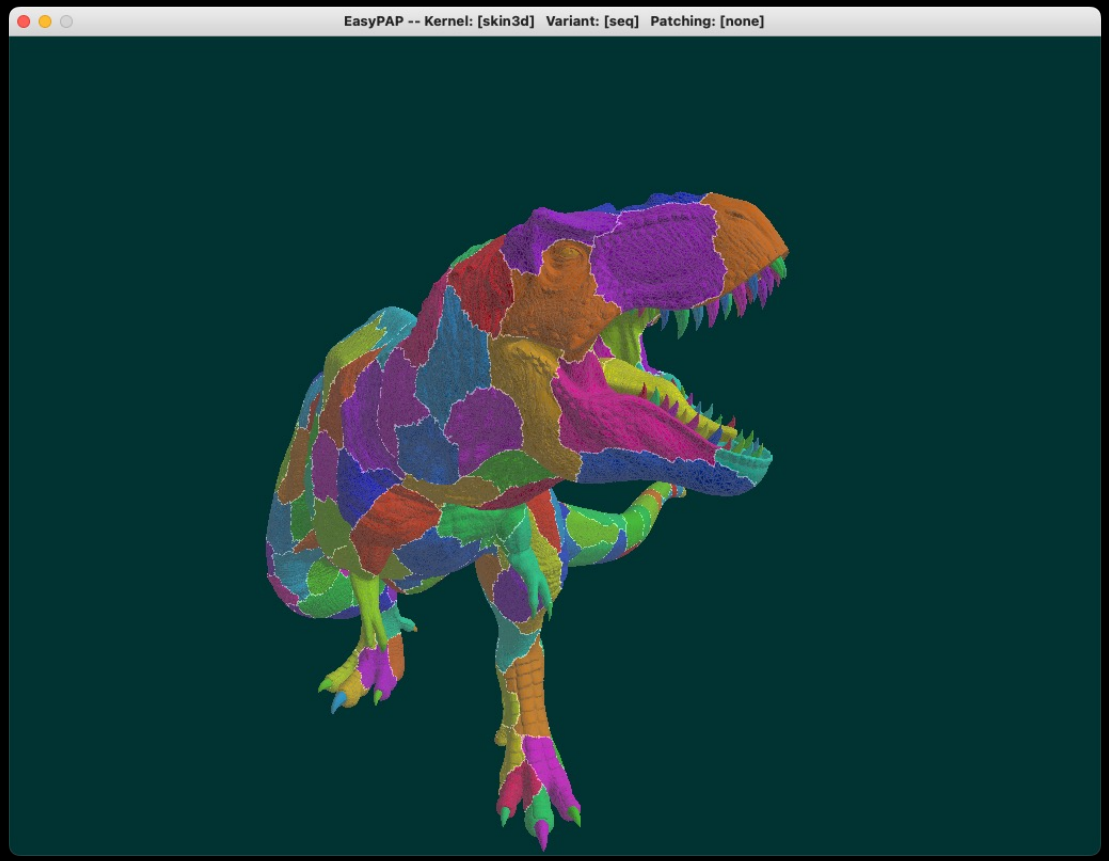
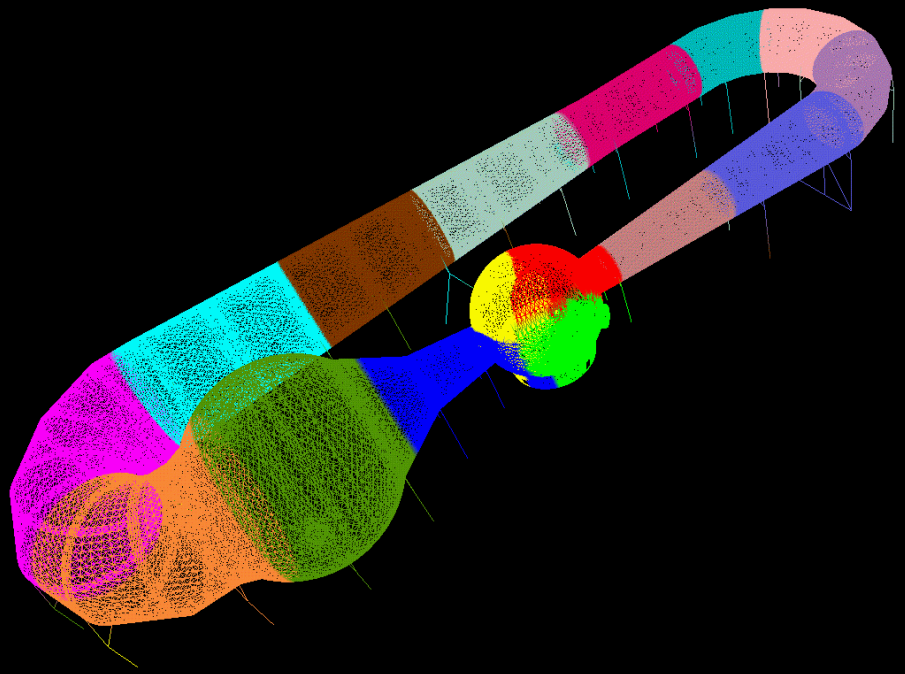


The Scotch Graph Partitioner

- Scotch is a graph partitioning library
  - F. Pellegrini, Univ. Bordeaux
- Scotch helps workload distribution
- Scotch is designed for parallel computing environments
  - offers multiple efficient and flexible algorithms
  - supports multiple graph formats



About partitions

- After the partitioning phase
  - Cells are sorted so that partitions are contiguous sets of cells numbers
- do_patch functions simply iterate on a subrange of cells

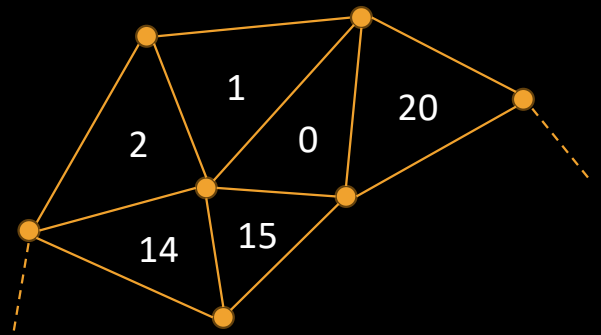
```
int sample3d_do_patch_default (int start_cell,
                               int end_cell)
{
  for (int c = start_cell; c < end_cell; c++)
    // Assign a value to each cell
    cur_data (c) = … ;

  return 0;
}

unsigned sample3d_compute_tiled (unsigned nb_iter)
{
  …
    for (int p = 0; p < NB_PATCHES; p++)
      do_patch (p);
  …
}
```

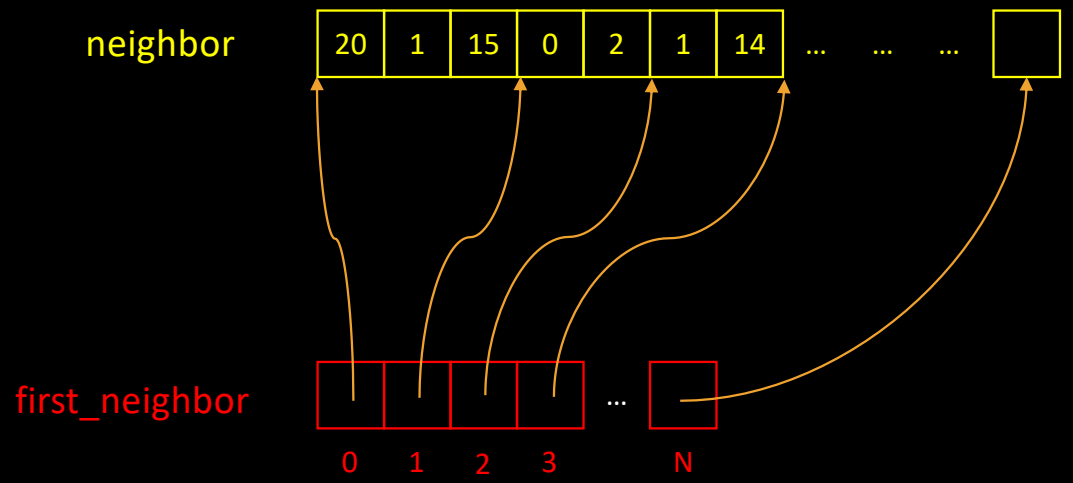
Accessing mesh connectivity

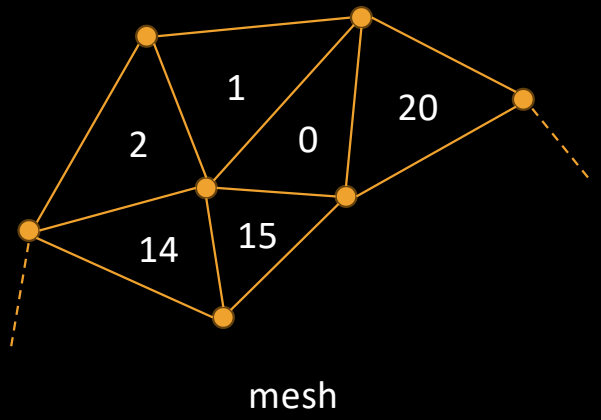
- In EasyPAP, the programmer sees
  - NB_CELLS
  - cur_data (cell) and next_data (cell)
- And
  - nb_neighbors (int cell)
  - nth_neighbor (int cell, int n)
  - max_neighbors ()
    - Max connectivity in the whole graph



mesh

Mesh connectivity:
a “compact edge array” is used by default

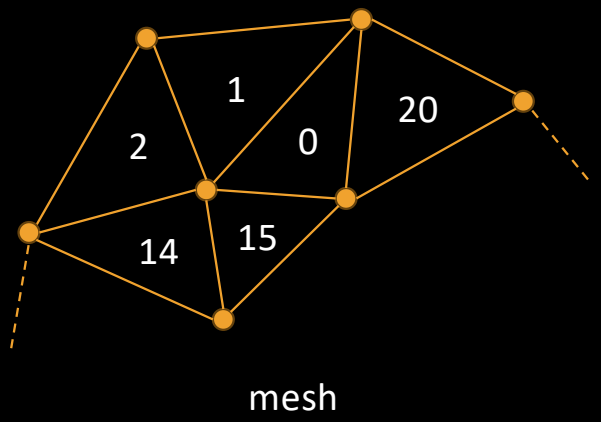




Neighbors of cell **i** are stored in: neighbors [first_neighbor[i] .. first_neightbor [i+1] – 1]

Mesh connectivity

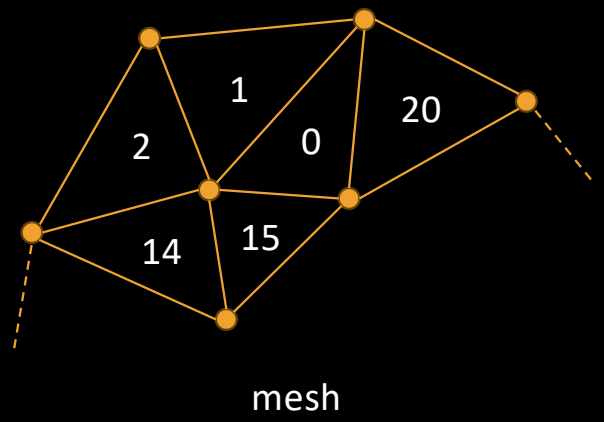
- Programmers can directly access the compact edge array
  - neighbor_start (int cell)
    - Index of first neighbor
  - neighbor_end (int cell)
    - Index of last neighbor + 1
  - neighbor (int index)



mesh

Accessing mesh connectivity in EasyPAP

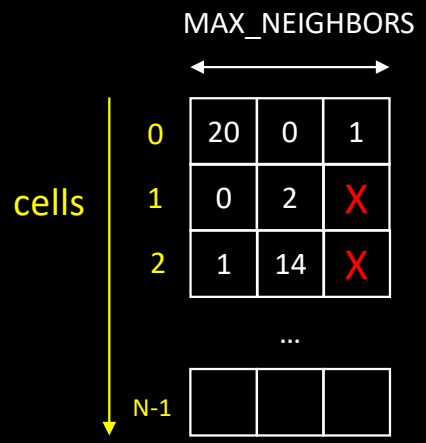
```
for (int nn = 0; nn < nb_neighbors (c); nn++) {
  int n = nth_neighbor (c, nn);
  float value = cur_data (n);
  …
}
// is equivalent to
for (int id = neighbor_start (c);
     id < neighbor_end (c); id++) {
  int n = neighbor (id);
  float value = cur_data (n);
  …
}
```

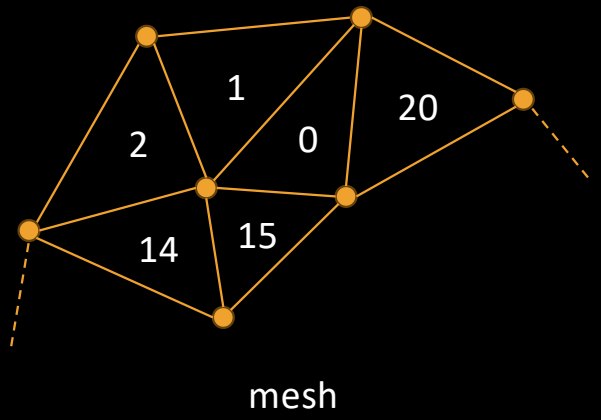


mesh

Towards a more regular data structure for GPUs and vector instructions

- Idea
  - We can waste a little space and use a 2D array!

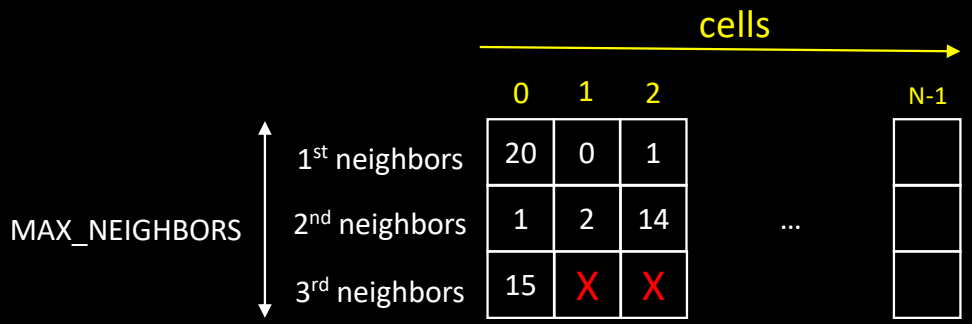


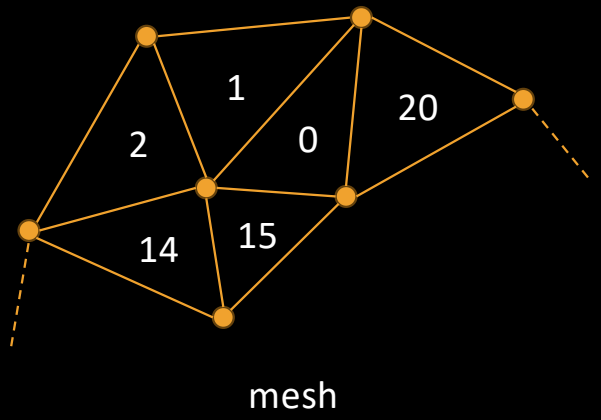


mesh

Towards a more regular data structure for GPUs and vector instructions

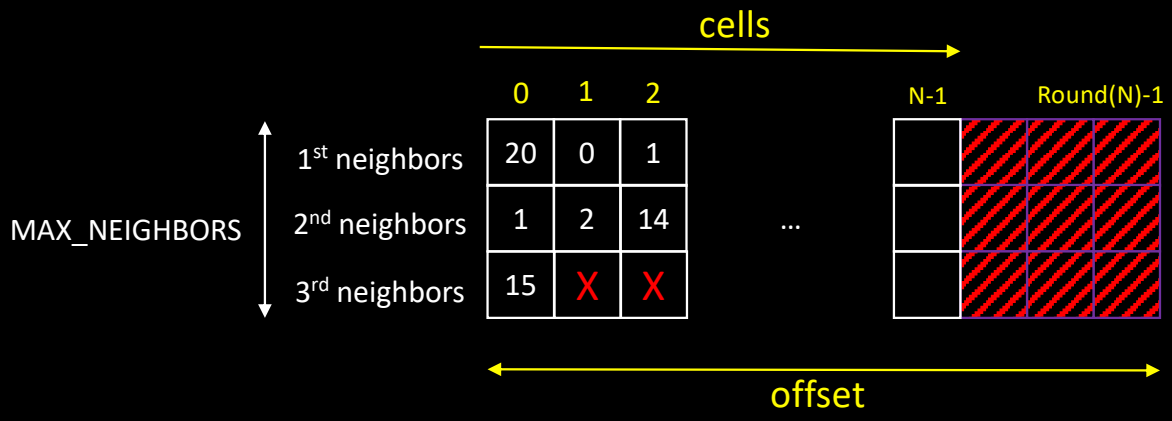
- Idea
  - Better use this data layout:

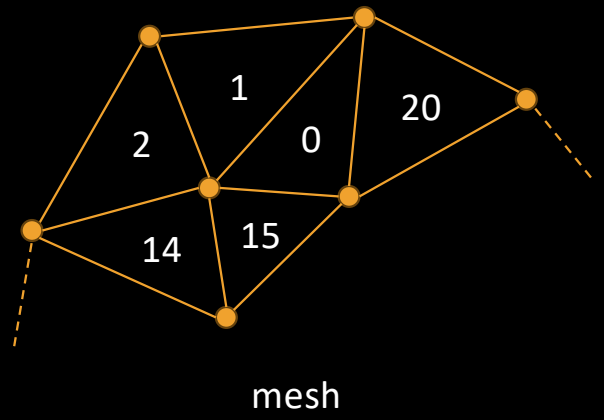




Towards a more regular data structure for GPUs and vector instructions

- Optimization
  - Use padding for alignment purposes





This is what is used by default in AVX and OpenCL implementations

Illustration with the max3d OpenCL kernel

```
__kernel void max3d_ocl (__global float *in, __global float *out,
                         __global __read_only int *neighbor)
{
  const int index = get_global_id (0);
  if (index < NB_CELLS) {
    float m = in [index];

    for (int n = 0; n < MAX_NEIGHBORS; n++) {
      int addr = neighbor [n * get_global_size (0) + index]; // good, coalesced access
      if (addr != -1) {
        float v = in [addr]; // bad, arbitrary access
        m = max (m, v);
      }
    }
    out [index] = m;
  }
}
```

Illustration with the max3d CUDA kernel

```
static __device__ void max3d_cuda (float *in, float *out, int *neighbor_soa,
                                   unsigned nb_cells, unsigned max_neighbors)
{
   int index = blockIdx.x * blockDim.x + threadIdx.x;
   int offset = blockDim.x * gridDim.x;
   if (index < nb_cells) {
      float m = in[index];
      for (int n = 0; n < max_neighbors; n++) {
         int addr = neighbor_soa[n * offset + index]; // good, coalesced access
         if (addr != -1) {
            float v = in [addr]; // bad, arbitrary access
            m = max (m, v);
         }
      }
      out[index] = m;
   }
}
```

Additional resources
available on
http://gforgeron.gitlab.io/pap/