Designing the Language Liszt

for Building Portable Mesh-based PDE Solvers

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Recap

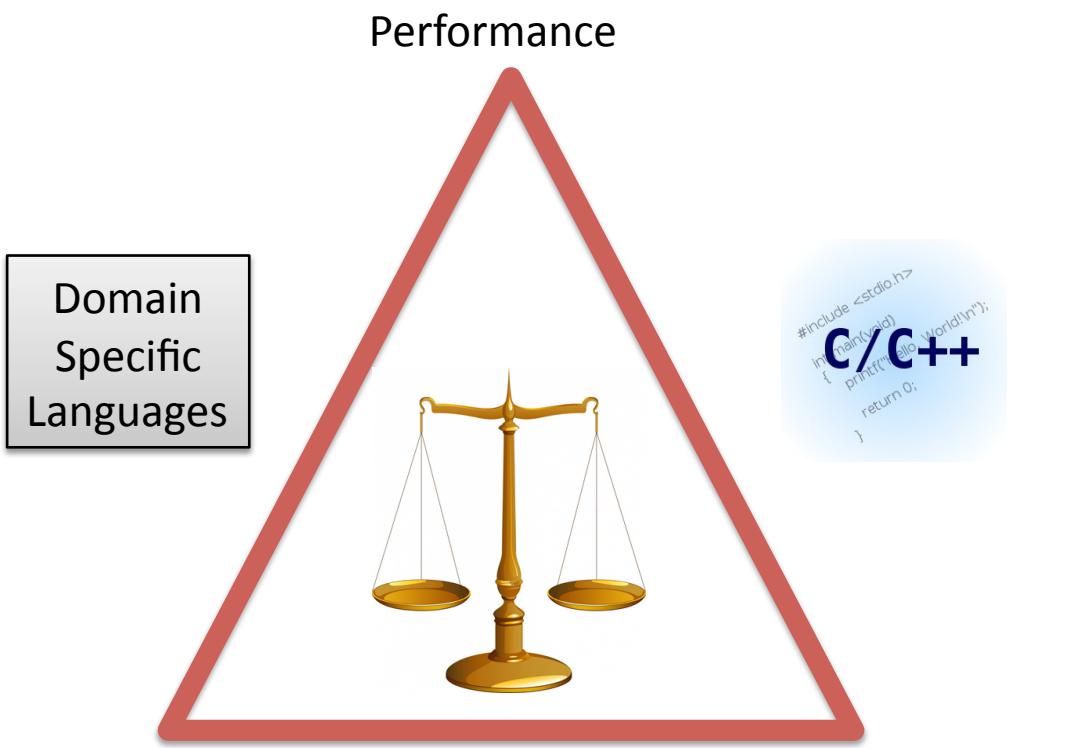
- ✓ Niels: Implementation of the Liszt compiler on clusters, SMPs, and GPUs
- ✓ Pat: history of co-design in graphics
- ✓ Crystal and Niels: Hands-on with Liszt at the Hackathon!
- ○ Today: Design of the Liszt language
  1. Insight into key design decisions we made
  2. Planned designs for new features and interoperability

Why use a DSL?

- Platform Independent
- More productive programming environment like R and MATLAB

- Specialize software like we specialize hardware

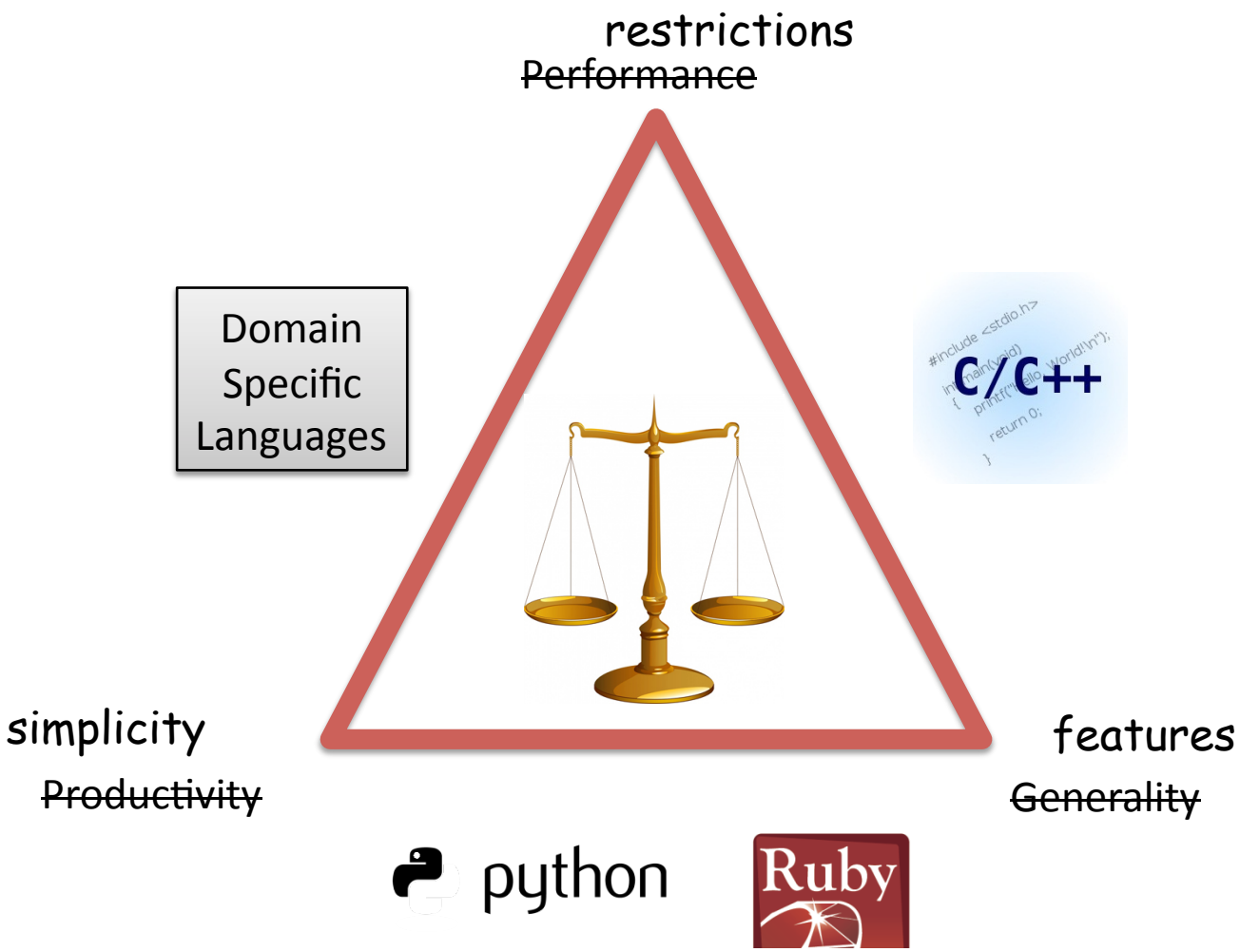
Successful Languages (portable)



python

Ruby

Successful Languages (portable)



Challenges

- Expressing the important problems
- Elegant and simple design
- Possible to implement efficiently and portably

Liszt: Heat Conduction on Grid

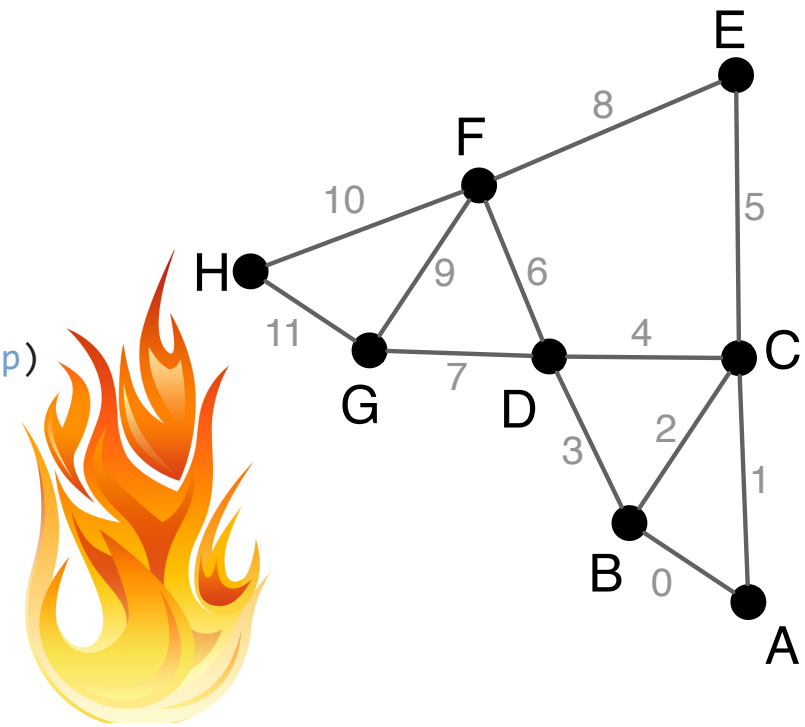
```
val Position = FieldWithLabel[Vertex,Float3](“position”)
val Temperature = FieldWithConst[Vertex,Float](0.0f)
val Flux = FieldWithConst [Vertex,Float](0.0f)
val JacobiStep = FieldWithConst[Vertex,Float](0.0f)
var i = 0;
while (i < 1000) {
  for (e <- edges(mesh)) {
    val v1 = head(e)
    val v2 = tail(e)
    val dP = Position(v1) - Position(v2)
    val dT = Temperature(v1) - Temperature(v2)
    val step = 1.0f/(length(dP))
    Flux(v1) += dT*step
    Flux(v2) -= dT*step
    JacobiStep(v1) += step
    JacobiStep(v2) += step
  }
  for (p <- vertices(mesh)) {
    Temperature(p) += 0.01f*Flux(p)/JacobiStep(p)
  }
  for (p <- vertices(mesh)) {
    Flux(p) = 0.f; JacobiStep(p) = 0.f;
  }
  i += 1
}
```

Mesh Elements

Topology Functions

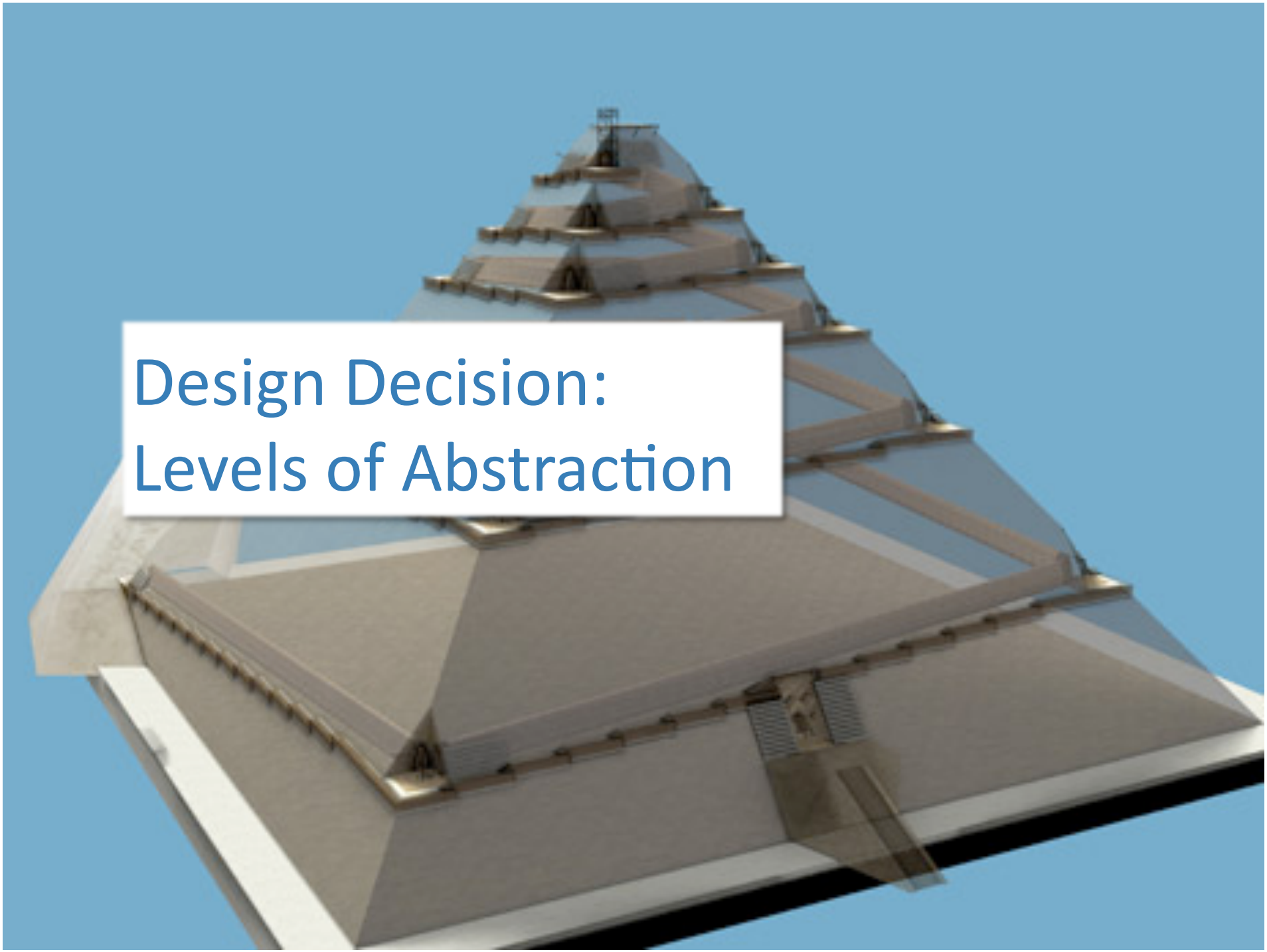
Fields (Data storage)

Parallelizable for



Design

1. Level of abstraction
   – Element-wise formulation
2. Representing the domain
   – Topological functions and fields
3. Finding data-dependencies
   – Inferring the data-dependencies from the stencil
4. Parallel Language Semantics



Design Decision: Levels of Abstraction

Level of Abstraction

- Continuous PDE

OpenFOAM

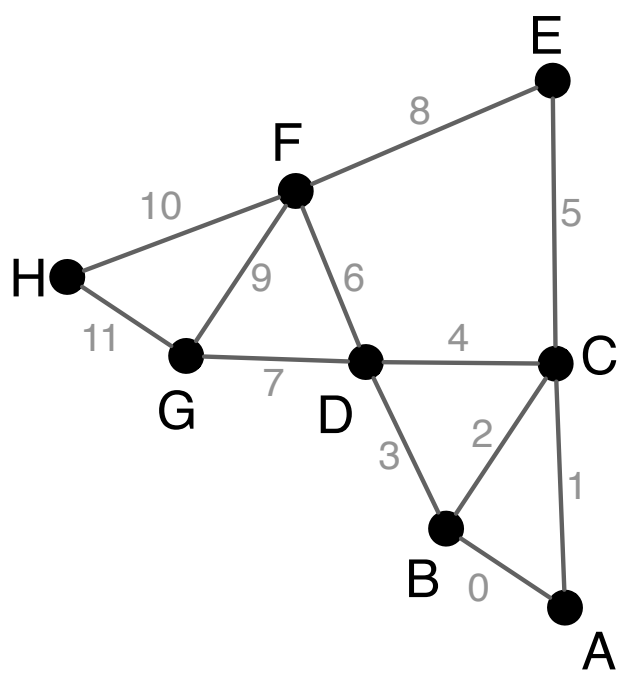
$$\frac{\partial \rho \mathbf{U}}{\partial t} + \nabla \cdot \phi \mathbf{U} - \nabla \cdot \mu \nabla \mathbf{U} = -\nabla p$$

```
solve
    (
        fvm::ddt(rho, U)
      + fvm::div(phi, U)
      - fvm::laplacian(mu, U)
        ==
      - fvc::grad(p)
    );
```

[OpenFOAM User Guide]

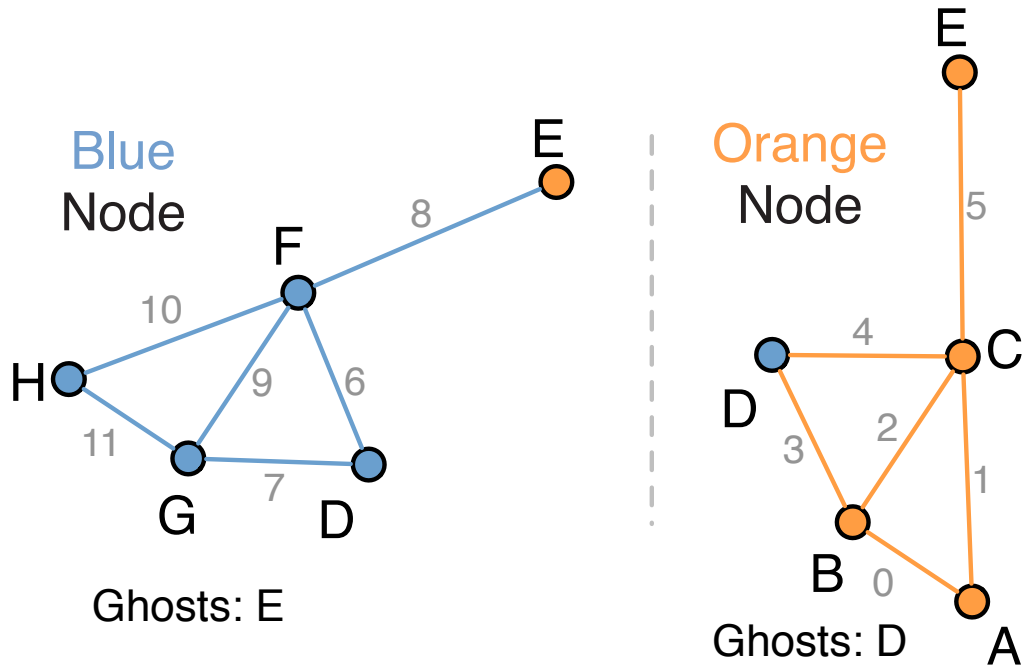
Level of Abstraction

- Element-wise Formulation: Liszt, OP2, Scout



Level of Abstraction

- Explicit Parallel Programming

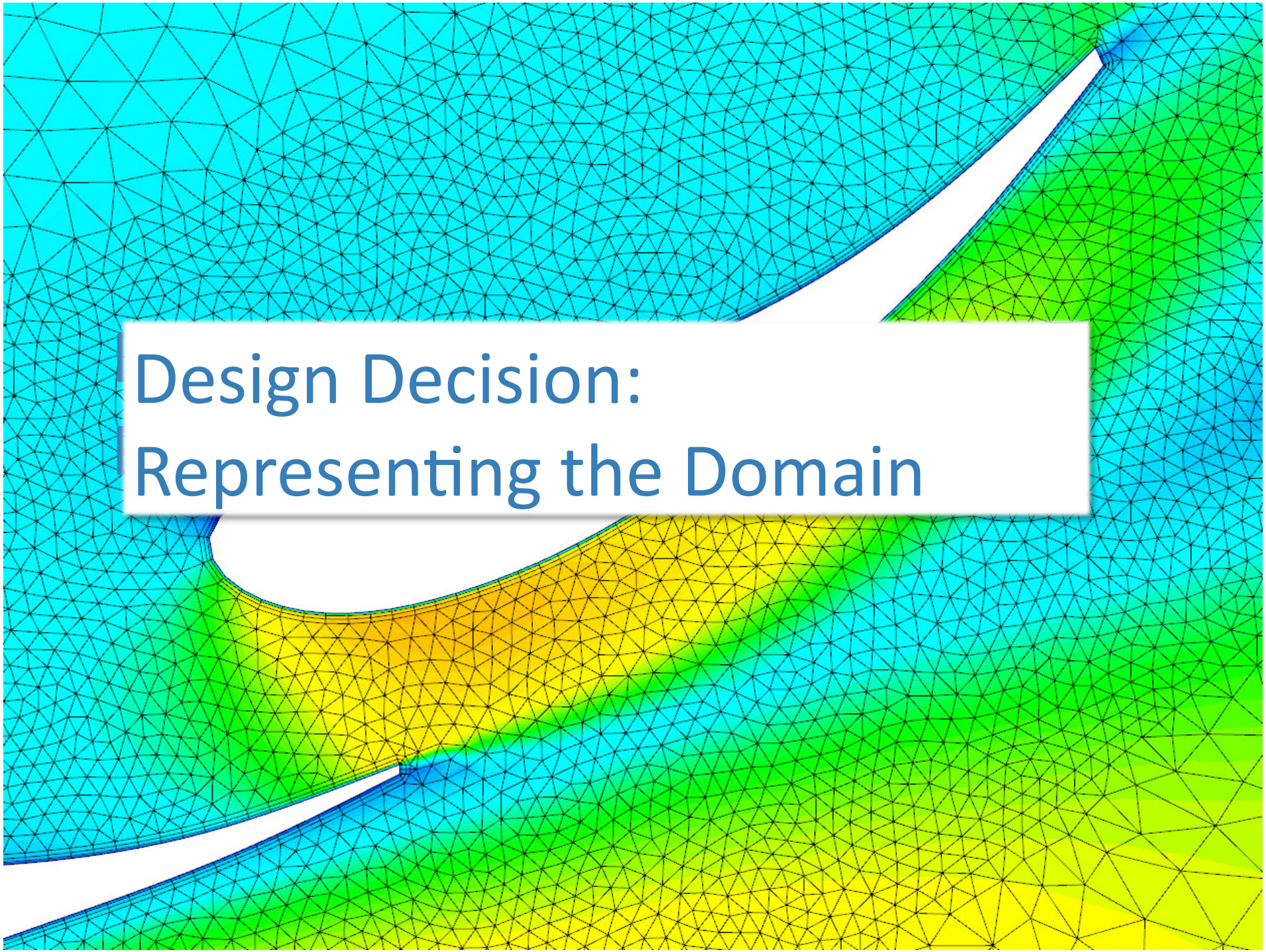



```
head_b[] = {F, G, E, F, H, G}
tail_b[] = {D, D, F, G, F, H}
```

```
head_o[] = {A, C, C, D, C, E}
tail_o[] = {B, A, B, B, D, C}
```

Level of Abstraction

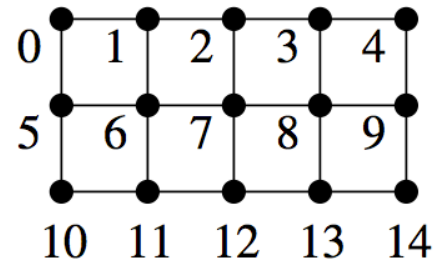
- Continuous PDE
  - ideal for already established numeric methods
- Explicit parallel programming
  - most flexibility, but limited portability to diverse architectures
- Element-wise formulation
  - much of the flexibility of explicit parallel programming
  - ability to run on multiple architectures



Design Decision: Representing the Domain

Representing the Domain

- Ad-hoc Storage



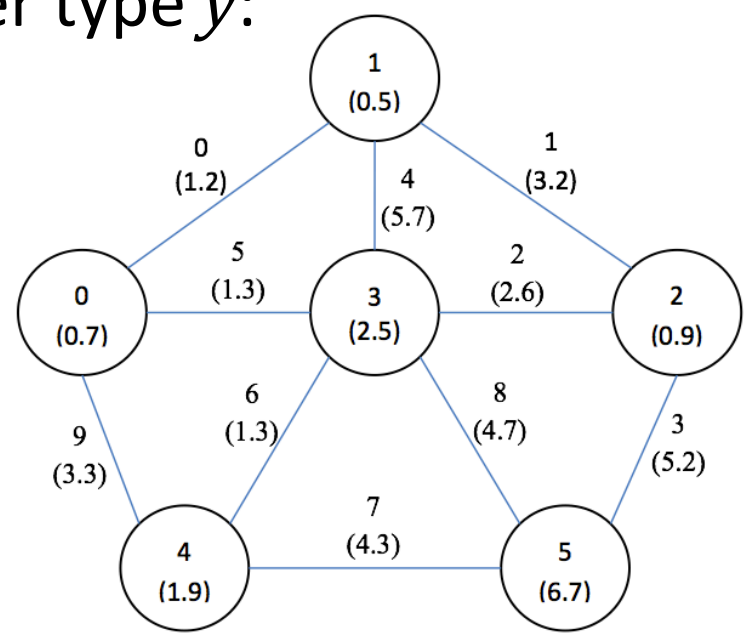
xadj	0 2 5 8 11 13 16 20 24 28 31 33 36 39 42 44
adjncy	1 5 0 2 6 1 3 7 2 4 8 3 9 0 6 10 1 5 7 11 2 6 8 12 3 7 9 13 4 8 14 5 11 6 10 12 7 11 13 8 12 14 9 13

[ParMETIS Manual]

```
for(int v = 0; v < N; v++) {
    int v_start = xadj[v];
    int v_end = xadj[v+1];
    for(int i = v_start; i < v_end; i++) {
        int v2 = adjncy[i];
        //...
    }
}
```

Representing the Domain

- Relations $r(x) = \{y_0, y_1, \ldots, y_N\}$
  - 1 to N mapping from user-defined element of type x to another type y:



[Giles et al.]

Representing the Domain

- Relations $r(x) = \{y_0, y_1, \ldots, y_N\}$

```
//create a relation from an edge to each of its vertices
int edge_map[20] = {1,2,2,3,3,4,3,6,2,4,1,4,4,5,6,5,4,6,1,5};
op_map pedge;
op_decl_map(
  edges /*set of edge objects*/,
  nodes /*set of node objects*/,
  2,    /*each edge has 2 nodes*/
  edge_map,/* the data */
  pedge /* pedge holds the relation*/
);
```

Representing the Domain

- Mesh Topology

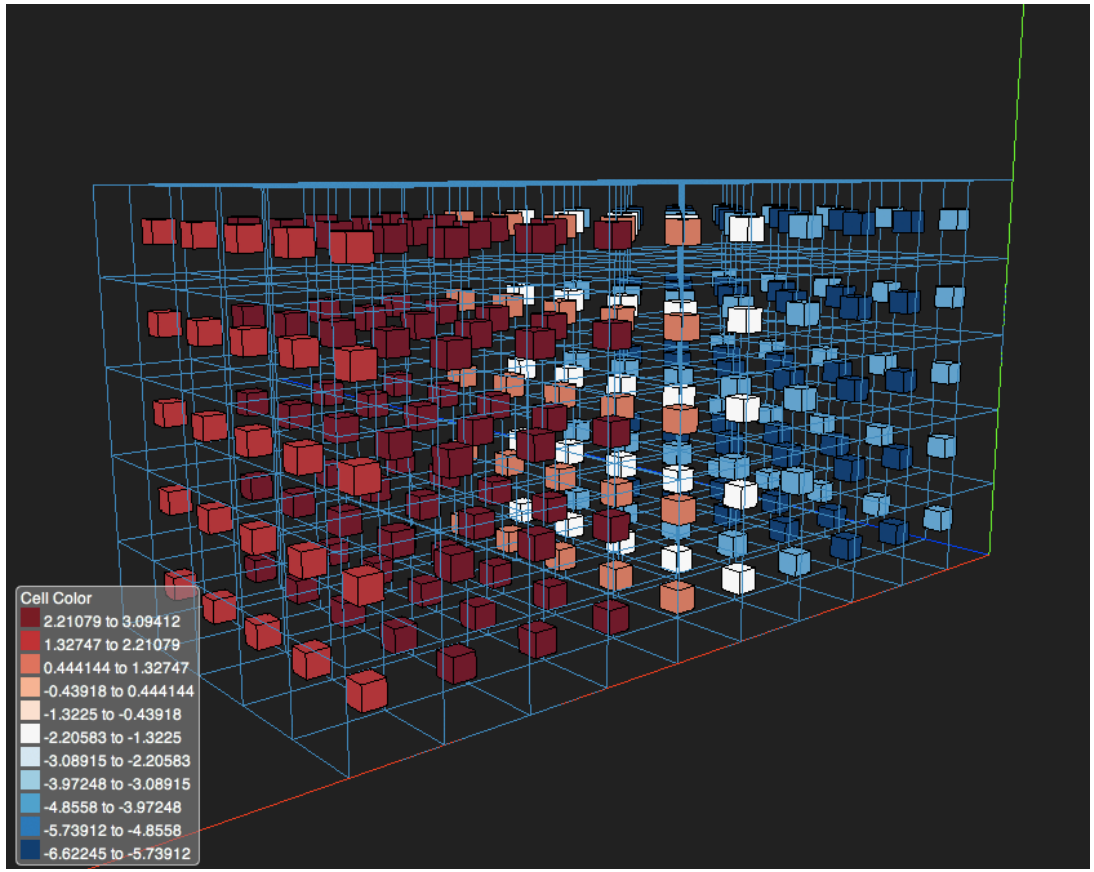
```
vertices(e : Vertex) : Set[Vertex]
cells(e : Vertex) : Set[Cell]
edges(e : Vertex) : Set[Edge]
faces(e : Vertex) : Set[Face]
```

```
cells(e : Cell) : Set[Cell]
vertices(e : Cell) : Set[Vertex]
faces(e : Cell) : Set[Face]
edges(e : Cell) : Set[Edge]
```

```
for(v <- vertices(mesh)) {
    for(v2 <- vertices(v)) {
        //...
    }
}
```

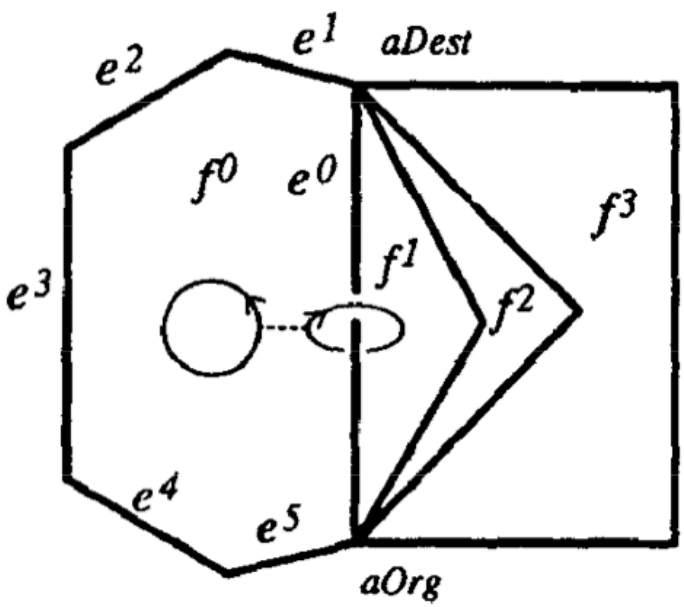
Why Meshes?

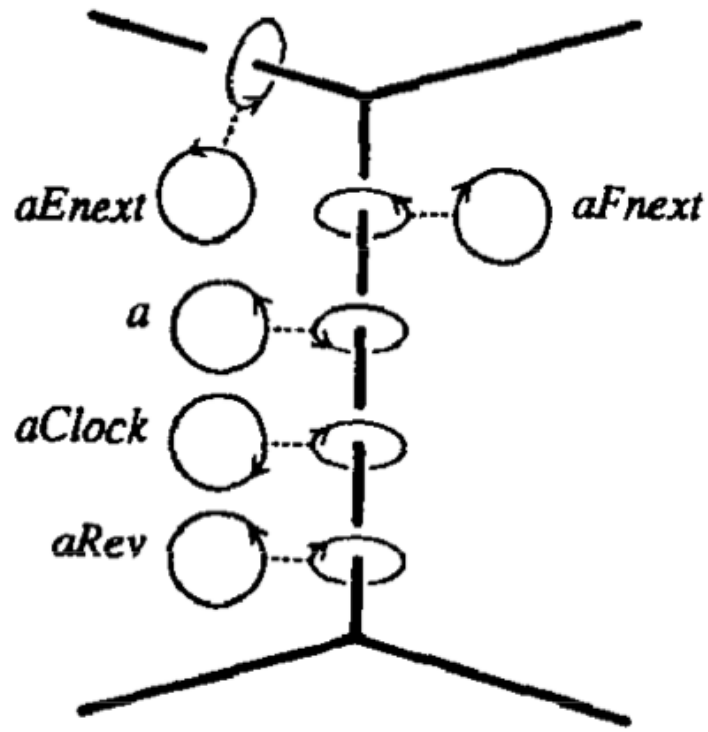
- Follows the way we visualize the domain



Why Meshes?

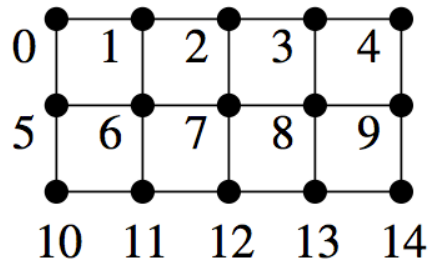
- More specific than a graph
  - we can use this for optimized data structures [Laszlo and Dobkin]





Why Meshes?

- Specialize code for different mesh types
  - Structured meshes:

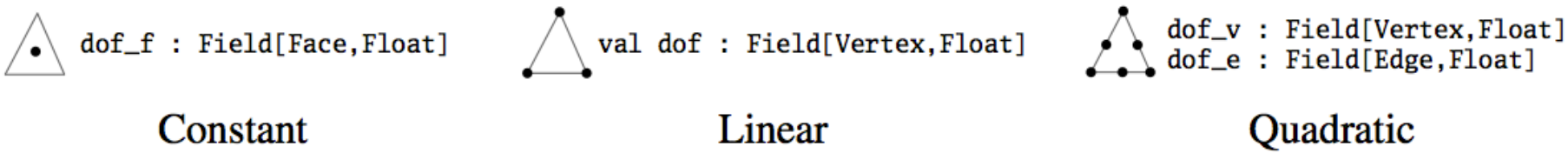



```
for(v <- vertices(v0)) {
    //...
}
```

```
int x0 = v0 % 5;
int y0 = v0 / 5;
for(int x = v0-1; x <= x0+1; x += 2) {
    for(int y = y0-1; y <= y0+1; y += 2)
    {
        int v = NC * y + x;
    }
}
```

Field-based Data Storage

- Mesh-based representation leads naturally to Liszt's fields
- Conceptually store the degrees of freedom for basis functions used to construct a continuous field



Design Decision: Expressing Data Dependencies

Data Dependencies

- Crucial to finding parallelism, exposing locality, and minimizing synchronization
- Determining data-dependencies in a general-purpose language is difficult and inaccurate

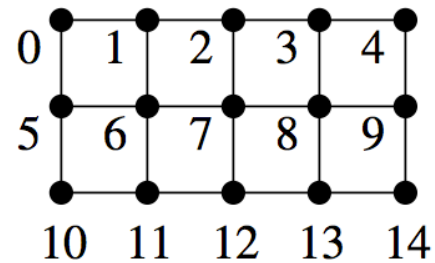
  A[i] = B[f(i)] – must compute f(i) to find dependency

Data Dependencies

- Explicitly provided by the user (OP2) [Giles et al.]

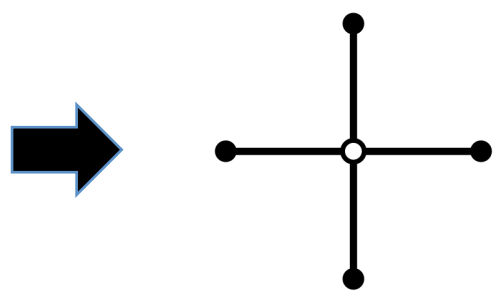
```
//create a relation from an edge to each of its vertices
int edge_map[20] = {1,2,2,3,3,4,3,6,2,4,1,4,4,5,6,5,4,6,1,5};
op_map pedge;
op_decl_map(
  edges /*set of edge objects*/,
  nodes /*set of node objects*/,
  2,    /*each edge has 2 nodes*/
  edge_map,/* the data */
  pedge /* pedge holds the relation*/
);
//run a function that specifies our relation as a dependency
op_par_loop_2(
  kernel, /* run function kernel */
  edges,  /* on all edges */
  temperature, 1,pedge, 2,"float", OP_READ,
    /* each edge with read the temperature data from both vertices*/
  flux, 0,pedge, 2,"float", OP_INC /* and update the flux data */
);
```

Data Dependencies



- Affine Partitioning
  - Addresses are affine transformations of variables x, y, and v0
  - Determine the stencil analytically [Lim and Lam]

```
int x0 = v0 % 5;
int y0 = v0 / 5;
for(int x = v0-1; x <= x0+1; x += 2) {
    for(int y = y0-1; y <= y0+1; y += 2) {
        A[v0] += B[NC * y + x];
    }
}
```

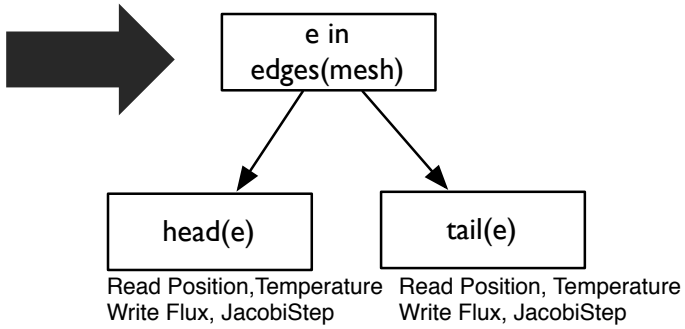


Stencil

Data Dependencies

- Inferring Dependencies from semantics of the mesh (Liszt)
  - can work for relations as well!

```
for (e <- edges(mesh)) {
  val v1 = head(e)
  val v2 = tail(e)
  val dP = Position(v1) - Position(v2)
  val dT = Temperature(v1) - Temperature(v2)
  val step = 1.0f/(length(dP))
  Flux(v1) += dT*step
  Flux(v2) -= dT*step
  JacobiStep(v1) += step
  JacobiStep(v2) += step
}
```



Data Dependencies

- Explicitly provided dependencies are verbose
- Affine partitioning only works for structured meshes
- Inferring dependencies based on mesh semantics address both issues

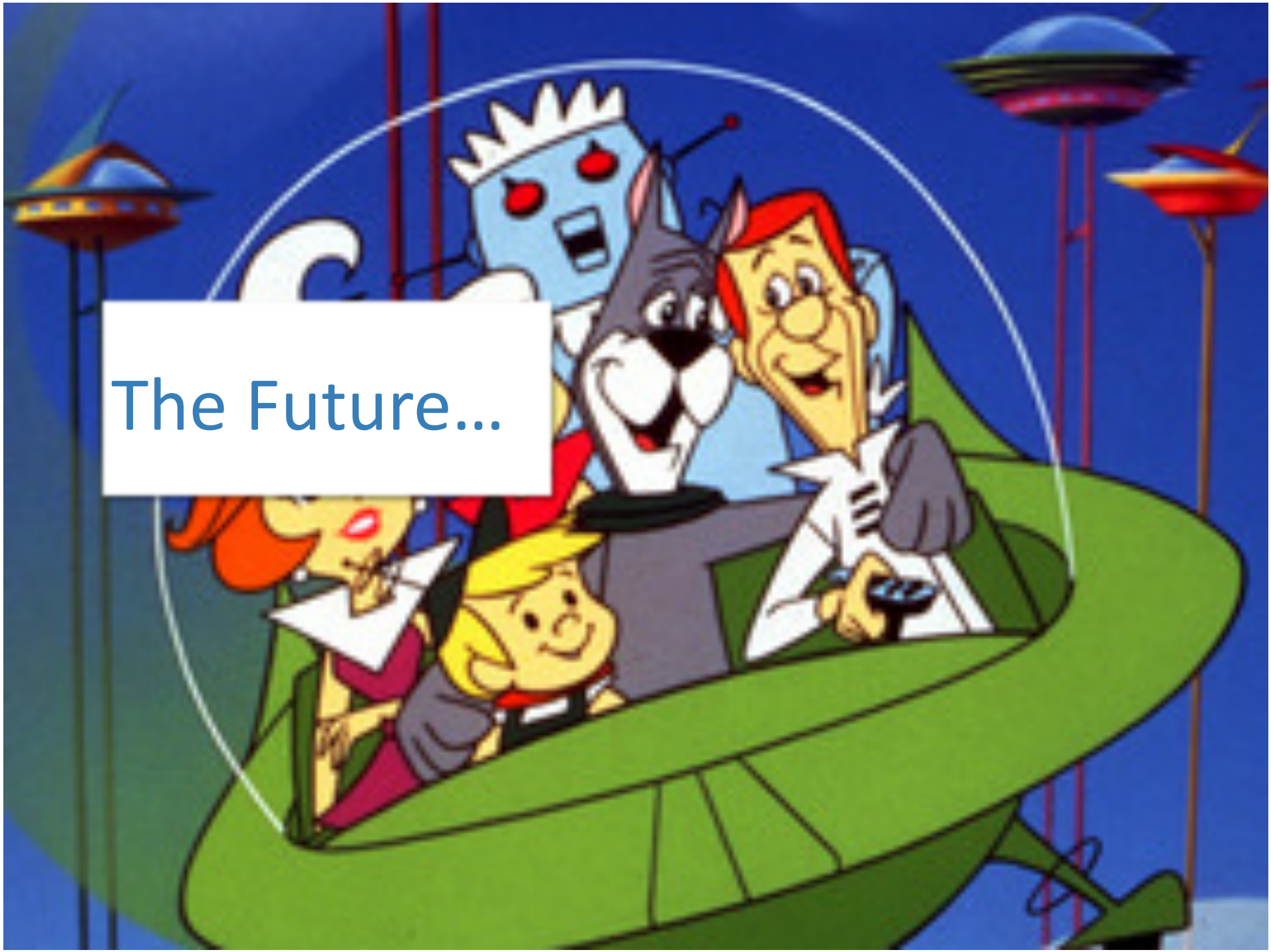
Parallel Language Semantics

Minimizing false dependencies

- Phased usage of Fields
  - Fields have *field phase* state
    - read-only, write-only, reduce-using-operator `field(el) [op]= value`
  - Fields cannot change phase within for-comprehension
- Associative Operators
  - Allow single expensive calculation to write data to multiple elements
  - Provide atomic scatter operations to fields
    - e. g. `field(el) += value`
  - Introduce write dependencies between instances of for-comprehension

Design

- Features
  - meshes, fields, topology functions, sets, for-comprehension
- Restrictions
  - parallel-for, associative reductions, field phases, immutable mesh variables
- Simplicity
  - built-in topological operators, simple fields

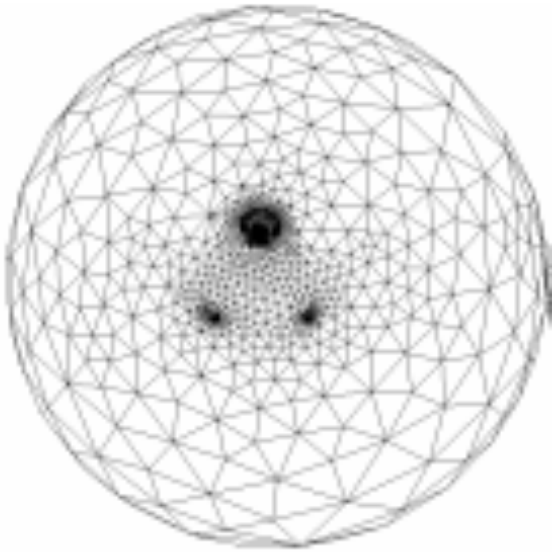

The Future…

Support More Applications

Interoperate with existing code

More Apps: Sparse Matrices

- Simple Example: Graph Layout

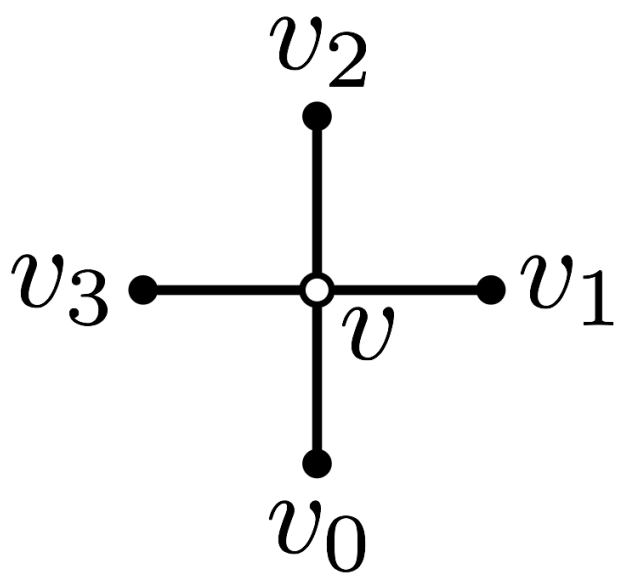


Tutte

[Images from Friedel et al.]

More Apps: Sparse Matrices

- Simple Example: Graph Layout
  - Tutte's spring embedding theorem:
    - Planar graph embedded in a convex polygon can be drawn without edge crossings by solving a linear system that places each vertex at the center of its neighbors



$$P_v - \frac{1}{N}\sum_{i=0}^{N} P_{v_i} = 0$$

More Apps: Sparse Matrices

```
object MyLS extends LinearSystem {
    def row(v : Vertex) : Vec[_2,RowIndex] = AutoIndex
    def col(v : Vertex) : Vec[_2,ColIndex] = AutoIndex
}
val A = MyLS.A(); val x = MyLS.x(); val b = MyLS.b()
<initialize boundary>
<initialize interior>
MyLS.solve(A,x,b)
```

More Apps: Sparse Matrices

```
    object MyLS extends LinearSystem {
        def row(v : Vertex) : Vec[_2,RowIndex] = AutoIndex
        def col(v : Vertex) : Vec[_2,ColIndex] = AutoIndex
    }
    val A = MyLS.A(); val x = MyLS.x(); val b = MyLS.b()
    <initialize boundary>
    <initialize interior>
    MyLS.solve(A,x,b)
    ----------------------------------------
<initialize boundary> ===
    for(v <- boundary) {
       val row = MyLS.row(v)
       val col = MyLS.col(v)
       val sz = size(vertices(v))
       A(row,col) = Mat(Vec(1.0,0.0), /* For brevity: Identity2x2 */
                        Vec(0.0,1.0))
       val pos : Double2 = position(v)
       b(row) = pos
    }
```

More Apps: Sparse Matrices

```
    object MyLS extends LinearSystem {
        def row(v : Vertex) : Vec[_2,RowIndex] = AutoIndex
        def col(v : Vertex) : Vec[_2,ColIndex] = AutoIndex
    }
    val A = MyLS.A(); val x = MyLS.x(); val b = MyLS.b()
    <initialize boundary>
    <initialize interior>
    MyLS.solve(A,x,b)
    ----------------------------------------
<initialize interior> ===
    for(v <- interior) {
        val row = MyLS.row(v)
        val col = MyLS.col(v)
        val N = size(vertices(v))
        A(row,col) = -Identity2x2 /* - P_v */
        for(v2 <- vertices(v)) {
            A(row,MyLS.col(v2)) = Identity2x2 / N /* + P_v2 / N */
        }
        b(row) = Vec(0.0,0.0) /* = 0 */
    }
```

Interoperate: Embedded DSLs

Interoperate: Embedded DSLs

- SQL

```
mysql_query(conn, "SELECT data FROM images WHERE id=1");
MYSQL_RES * result = mysql_store_result(conn);
int num_fields = mysql_num_fields(result);
MYSQL_ROW row;
while ( row = mysql_fetch_row(result) ) {
    for(int i = 0; i < num_fields; i++) {
        printf("%s\t",row[i]);
        printf("\n");
    }
}
```

Embedded DSLs

- OpenGL

```
char * shader =
"void main()"
"{"
"   gl_FragColor ="
"    vec4(0.4,0.4,0.8,1.0);"
"}";

GLuint f =
glCreateShader(GL_FRAGMENT_SHADER);
glShaderSource(v, 1, &shader,NULL);
glCompileShader(f);

GLuint p = glCreateProgram();
glAttachShader(p,f);
glLinkProgram(p);
glUseProgram(p);
```

```
glBegin(GL_TRIANGLES);
    glVertex3f( 0.0f, 1.0f, 0.0f);
    glVertex3f(-1.0f,-1.0f, 0.0f);
    glVertex3f( 1.0f,-1.0f, 0.0f);
glEnd();
```

Embedded DSLs

- Lua – Game Scripting

```
if (IsPartyLeader()) then
  ChatFrame1:AddMessage("I am the leader of my party!")
end
```

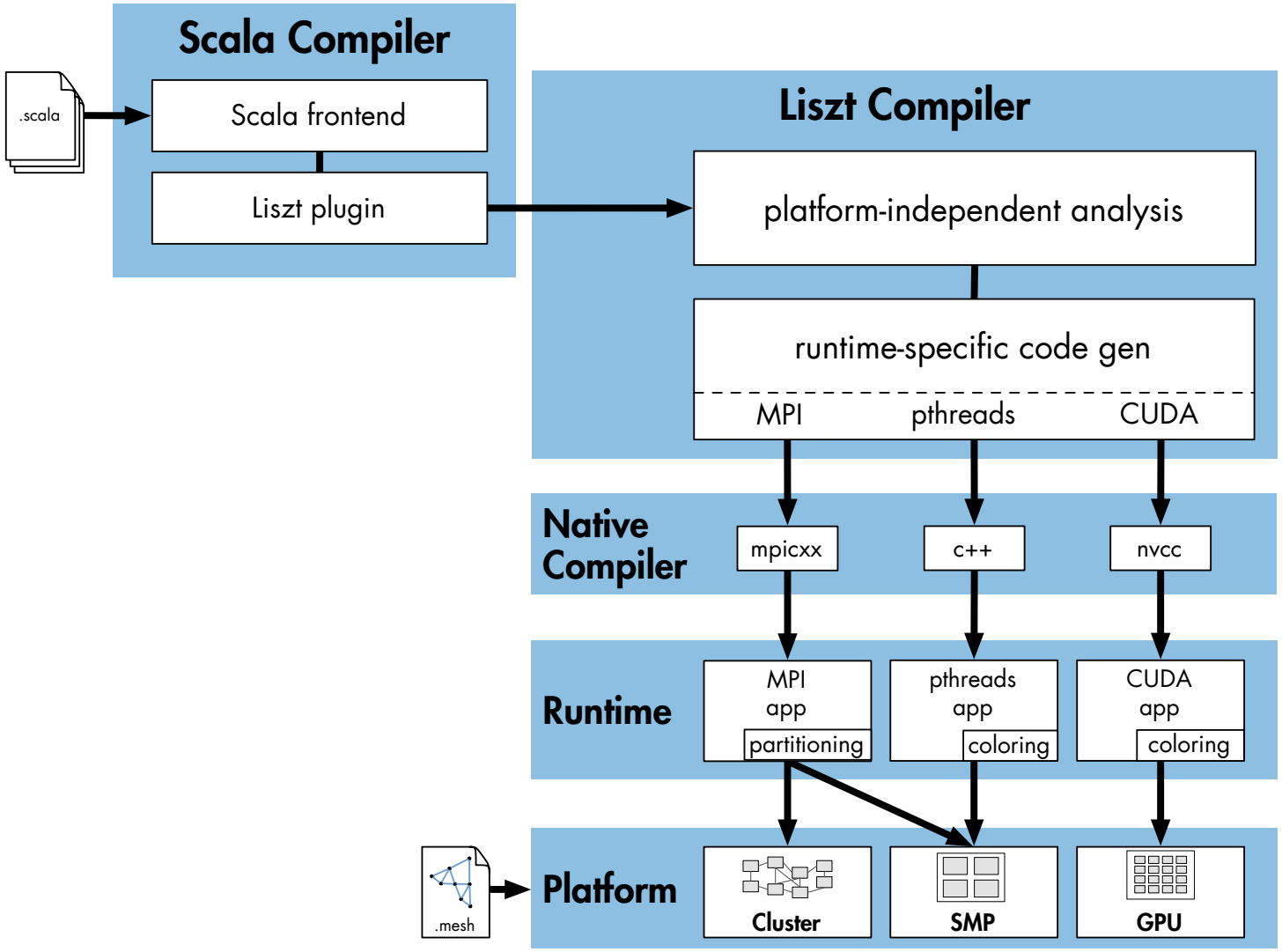
Embedded DSLs

- Lua – Embedded by design
  - Lua: “Passing a Language through the Eye of a Needle” [Roberto Ierusalimschy, Luiz Henrique de Figueiredo, Waldemar Celes]

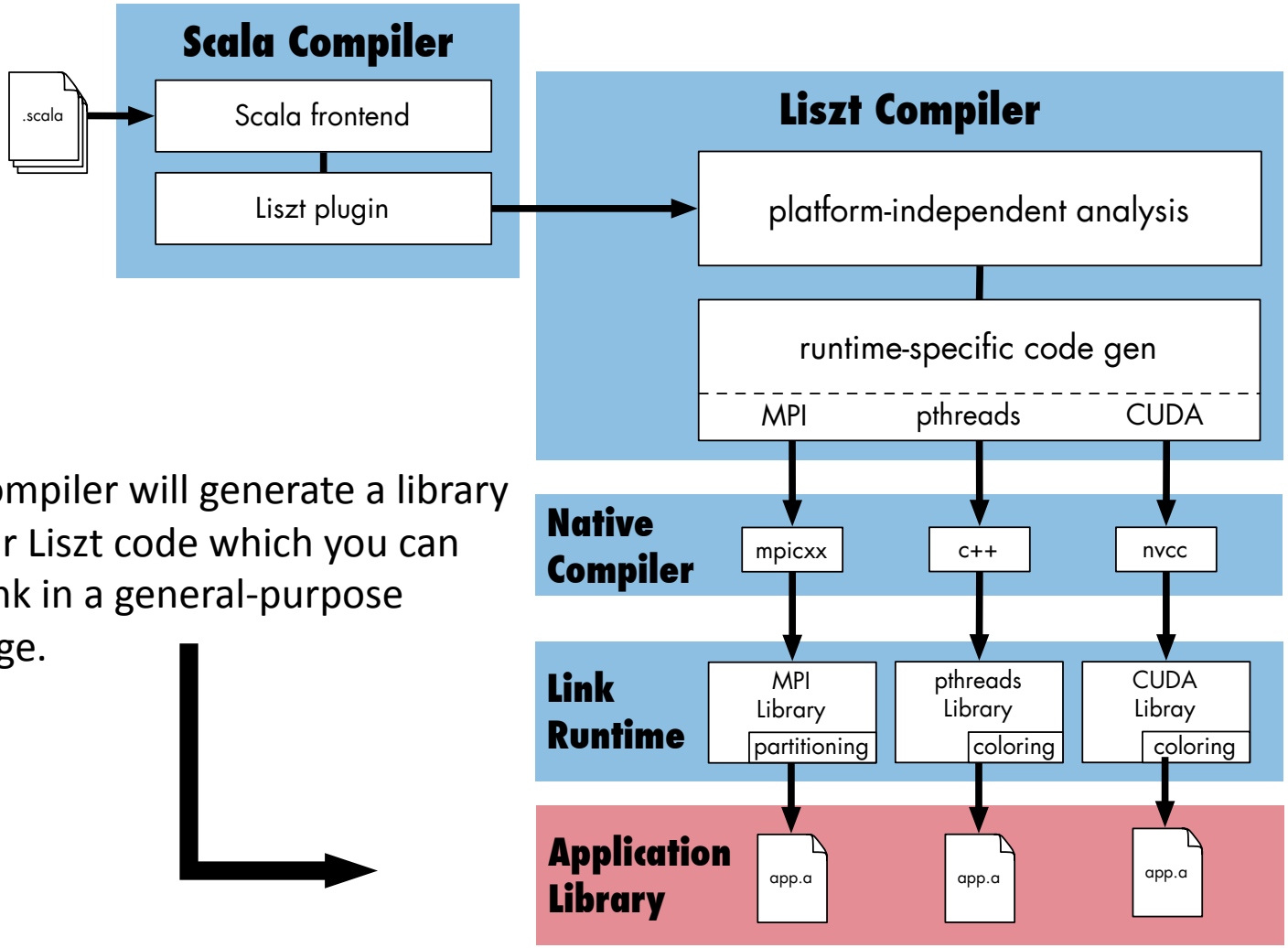
```
lua_State *L = luaL_newstate(); /* create a new state */
luaL_openlibs(L); /* open the standard libraries */

/* reads lines and executes them */
while (fgets(line, sizeof(line), stdin) != NULL) {
    luaL_loadstring(L, line); /* compile line to a function */
    lua_pcall(L, 0, 0, 0); /* call the function */
}
```

Liszt as an Embedded DSL



Liszt as an Embedded DSL



Liszt compiler will generate a library for your Liszt code which you can then link in a general-purpose language.

Liszt as an Embedded DSL

```
val Position = Field[Vertex,Float3] /* value is not specified! */
val Temperature = Field[Vertex,Float](0.0f) /* value is not specified! */
val Flux = FieldWithConst[Vertex,Float](0.0f)
val JacobiStep = FieldWithConst[Vertex,Float](0.0f)
@entry def calculate_temperature() {
    var i = 0;
    while (i < 1000) {
      for (e <- edges(mesh)) {
        val v1 = head(e)
        val v2 = tail(e)
        val dP = Position(v1) - Position(v2)
        val dT = Temperature(v1) - Temperature(v2)
        val step = 1.0f/(length(dP))
        Flux(v1) += dT*step
        Flux(v2) -= dT*step
        JacobiStep(v1) += step
        JacobiStep(v2) += step
      }
      for (p <- vertices(mesh)) {
         Temperature(p) += 0.01f*Flux(p)/JacobiStep(p)
      }
      for (p <- vertices(mesh)) {
        Flux(p) = 0.f; JacobiStep(p) = 0.f;
      }
      i += 1
   }
}
```

Liszt as an Embedded DSL

```
/* recall: Temperature and Position weren't initialized in Liszt */

double * temperature_data
  = MyLoadData("my_initial_temperatures.dat")
LisztMesh mesh;
Liszt_load_fluent_mesh("myfluentfile.msh",&mesh);
Liszt_bind_mesh(mesh);
Liszt_load_field(temperature_data,"Temperature"); //load temperature
Liszt_load_field_as_position("Position"); //load position
Liszt_execute("calculate_temperature");

double * calculated_temperature;
Liszt_read_field(calculated_temperature,"Temperature");
```

Summary

- Balance features, restrictions, and simplicity
  - Element-wise formulation
  - Mesh-based topological functions and storage
  - Inferred dependencies
- Future:
  - expand the language to new problems
  - interface with existing languages