Introduction to DSLs

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Simulation

- Levels
    - Maths
    - Discretisation
    - Algorithm
    - Implementation

Application scientist

Numericist

HPC expert

Abstract Description

Concrete Implementation

- Schulthess, T. Programming revisited. *Nature Phys* 11, 369–373 (2015). https://doi.org/10.1038/nphys3294

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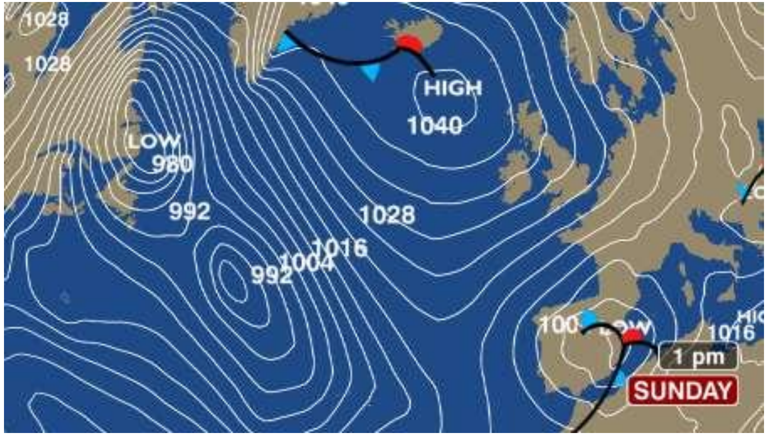
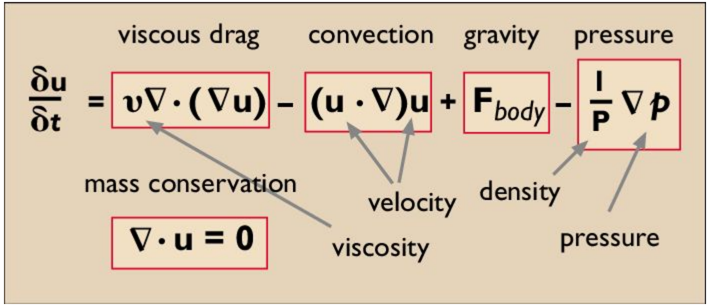
Worked example: Computing a gradient

- Why? Frequently used in Weather and Climate models

- For example: tightly packed isobars (pressure gradient) means strong winds
- Wind acceleration is proportional to pressure gradient





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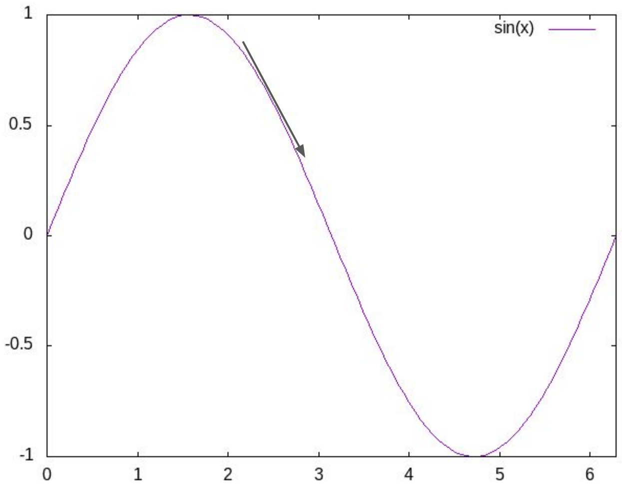
Maths level



$$grad f = \nabla f$$

https://www.youtube.com/watch?v=M0u9Qy3SERI

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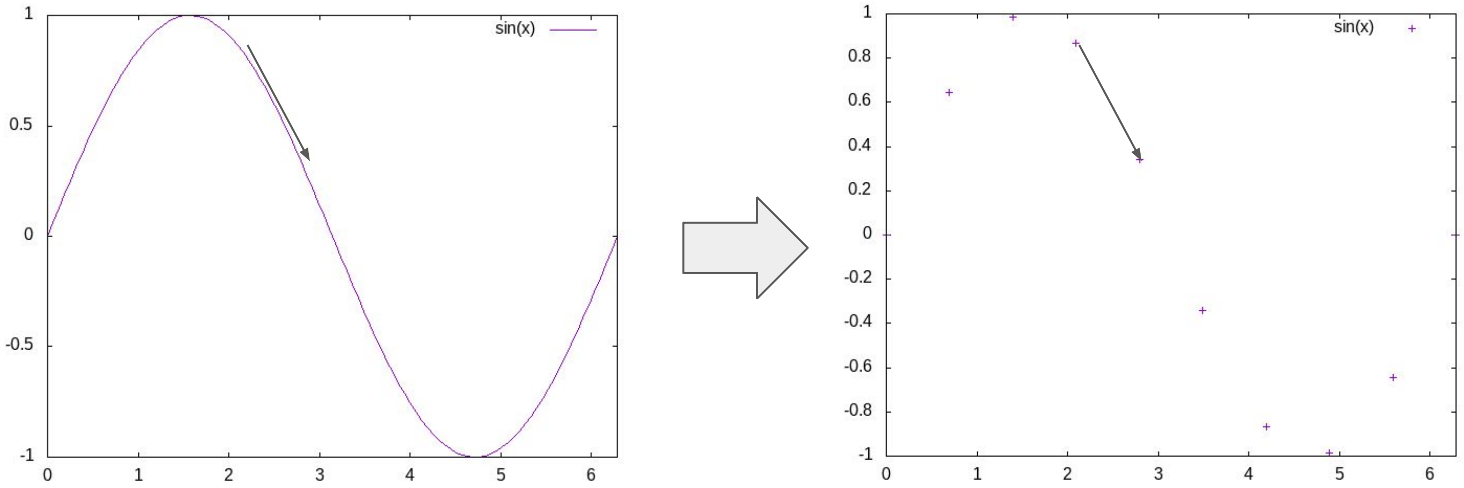
Discretisation level

- Choose finite elements, finite volume, finite difference

https://www.youtube.com/watch?v=9WE4zKCLxW8



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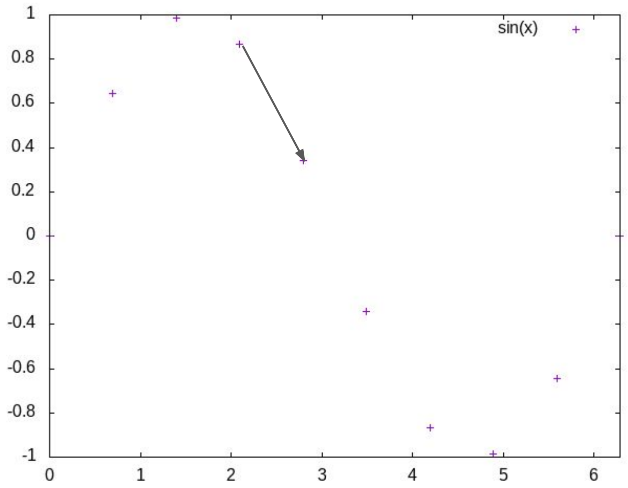
Algorithm level

Compare with calculus ...

- Choose multigrid, order of the scheme, etc.
- Different ways to work out gradient
- Here we use a simple 1st order scheme



$$f'(a) = \lim_{h \to 0} \frac{f(a+h) - f(a)}{h}$$

$$\underline{\nabla}_{\underline{n}}\psi(e) = \frac{\psi(c_1(e)) - \psi(c_0(e))}{\hat{l}}$$

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Implementation level

- This is what is compiled and run
- Code taken from the ICON model
- 3D mesh
- Fortran

$$\underline{\nabla}_{\underline{n}}\psi(e) = \frac{\psi(c_1(e)) - \psi(c_0(e))}{\hat{l}}$$

```
DO jk = slev, elev
 DO je = i_startidx, i_endidx
   grad_norm_psi_e(je,jk) =
      (psi_c(iidx(je,2),jk)-psi_c(iidx(je,1),jk))/lhat(je)
 ENDDO
END DO
```

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Running fast/parallel

- Original serial code
- (very) straight forward implementation
- "actual science" + mesh

```
DO jk = slev, elev
 DO je = i_startidx, i_endidx
   grad_norm_psi_e(je,jk) =
      (psi_c(iidx(je,2),jk)-psi_c(iidx(je,1),jk))/lhat(je)
 ENDDO
END DO
```

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Running fast/parallel

- turns out that the mesh is too large for one machine and therefore runs slowly, so add blocks

```
DO jb = i_startblk, i_endblk
 CALL get_indices_e(ptr_patch, jb, i_startblk, i_endblk, &
                   i_startidx, i_endidx, rl_start, rl_end)
 DO jk = slev, elev
   DO je = i_startidx, i_endidx
     grad_norm_psi_e(je,jk,jb) =  &
       ( psi_c(iidx(je,jb,2),jk,iblk(je,jb,2)) -
         psi_c(iidx(je,jb,1),jk,iblk(je,jb,1)) )
       / ptr_patch%edges%lhat(je,jb)
   ENDDO
 END DO
END DO
```

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Running fast/parallel

- add directives to exploit multiple cores on shared memory machines

```
#ifdef _OMP
!$OMP PARALLEL
!$OMP DO PRIVATE(jb, i_startidx, i_endidx, je, jk)
#endif
DO jb = i_startblk, i_endblk
 CALL get_indices_e(ptr_patch, jb, i_startblk, i_endblk, &
                    i_startidx, i_endidx, rl_start, rl_end)
 DO jk = slev, elev
   DO je = i_startidx, i_endidx
     grad_norm_psi_e(je,jk,jb) =  &
       ( psi_c(iidx(je,jb,2),jk,iblk(je,jb,2)) -
         psi_c(iidx(je,jb,1),jk,iblk(je,jb,1)) )
       / ptr_patch%edges%lhat(je,jb)
   ENDDO
 END DO
END DO
#ifdef _OMP
!$OMP END DO NOWAIT
!$OMP END PARALLEL
#endif
```

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Running fast/parallel

- code also needs to target an architecture with a GPU accelerator ...
- ... which has a different optimal memory layout

```
#ifdef _OMP
!$OMP ....
#else
!$ACC ....
#endif
DO jb = i_startblk, i_endblk
 CALL get_indices_e(ptr_patch, ...)
 #ifdef __LOOP_EXCHANGE
 DO je = i_startidx, i_endidx
   DO jk = slev, elev
 #else
   DO jk = slev, elev
     DO je = i_startidx, i_endidx
 #endif
     grad_norm_psi_e(je,jk,jb) =  &
       ( psi_c(iidx(je,jb,2),jk,iblk(je,jb,2)) -
         psi_c(iidx(je,jb,1),jk,iblk(je,jb,1)) )
       / ptr_patch%edges%lhat(je,jb)
   ENDDO
 END DO
END DO
#ifdef _OMP
!$OMP ...
#else
!$ACC ...
#endif
```

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Running fast/parallel

$$\underline{\nabla}_{\underline{n}}\psi(e) = \frac{\psi(c_1(e)) - \psi(c_0(e))}{\hat{l}}$$

```
#ifdef _OMP
!$OMP ....
#else
!$ACC ....
#endif
DO jb = i_startblk, i_endblk
 CALL get_indices_e(ptr_patch, ...)
 #ifdef __LOOP_EXCHANGE
 DO je = i_startidx, i_endidx
   DO jk = slev, elev
 #else
   DO jk = slev, elev
     DO je = i_startidx, i_endidx
 #endif
     grad_norm_psi_e(je,jk,jb) =  &
       ( psi_c(iidx(je,jb,2),jk,iblk(je,jb,2)) -
        psi_c(iidx(je,jb,1),jk,iblk(je,jb,1)) )
       / ptr_patch%edges%lhat(je,jb)
   ENDDO
 END DO
END DO
#ifdef _OMP
!$OMP ...
#else
!$ACC ...
#endif
```

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Running fast/parallel

What if

- Requirements change, e.g. it turns out that this gradient should have been approximated using a higher order stencil?
- A third (fourth...) architecture needs to be supported?
- The mesh library needs to be replaced?
- Loops should be fused together for greater performance on a particular architecture?
- A compiler has a bug that needs a workaround?

```
#ifdef _OMP
!$OMP ....
#else
!$ACC ....
#endif
DO jb = i_startblk, i_endblk
 CALL get_indices_e(ptr_patch, ...)
 #ifdef __LOOP_EXCHANGE
 DO je = i_startidx, i_endidx
   DO jk = slev, elev
 #else
   DO jk = slev, elev
     DO je = i_startidx, i_endidx
 #endif
     grad_norm_psi_e(je,jk,jb) =  &
       ( psi_c(iidx(je,jb,2),jk,iblk(je,jb,2)) -
         psi_c(iidx(je,jb,1),jk,iblk(je,jb,1)) )
       / ptr_patch%edges%lhat(je,jb)
   ENDDO
 END DO
END DO
#ifdef _OMP
!$OMP ...
#else
!$ACC ...
#endif
```

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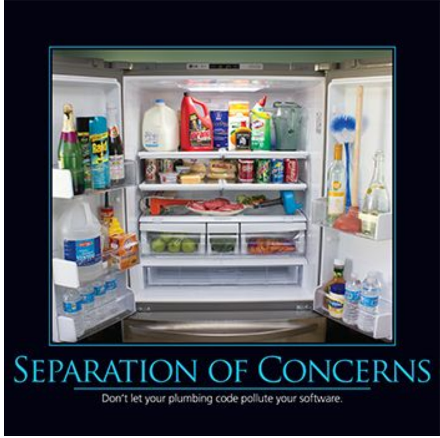
Separation of Concerns



- Performance portable maintainable code is difficult to achieve

  What can we do?

- Can we separate the specification/coding of the science from its optimisation?
- This would
  - allow the scientists to concentrate on developing the science
  - Allow HPC experts to concentrate on optimising the code

  Domain-specific languages (DSLs) offer a way to do this ...

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Domain Specific Languages

- Languages tailored to a (very) specific purpose
  - as opposed to general purpose programming languages like C, C++, Java, Python...
- This definition is quite general and includes things like:
  - HTML for web pages
  - PostScript for documents
  - MATLAB for maths processing
- However, we focus on DSLs for High Performance Computing (HPC)

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Domain Specific Languages

- DSL Frameworks are becoming a more and more viable approach for device-specific code generation, often achieving performance numbers unatainable for general purpose compilers
- Since DSLs are, well, domain specific, they are very expressive for the domain they are tailored to
  - shorter code, better maintainability
- Some application domains for HPC using DSLs include
  - Image Processing (Halide)
  - Deep Learning (XLA)
  - Climate & Numerical Weather Prediction (Stella, Gridtools, dawn, PSyclone)

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Benefit of DSL vs coding

The DSL Idea

$$\underline{\nabla_n}\psi(e) = \frac{\psi(c_1(e)) - \psi(c_0(e))}{\hat{l}}$$

```
grad_norm_psi_e =
      reduce( psi_c,
              CELL > EDGE,
              [1/lhat, -1/lhat]
           )
```

OMP

DSL compiler

```
!$OMP PARALLEL
!$OMP DO PRIVATE(jb, i_startidx, i_endidx, je, jk)
DO jb = i_startblk, i_endblk
 CALL get_indices_e(ptr_patch, ...)
 DO je = i_startidx, i_endidx
   DO jk = slev, elev
     grad_norm_psi_e(je,jk,jb) =  &
       ( psi_c(iidx(je,jb,2),jk,iblk(je,jb,2)) -
         psi_c(iidx(je,jb,1),jk,iblk(je,jb,1)) )
       / ptr_patch%edges%lhat(je,jb)
   ENDDO
 END DO
END DO
!$OMP END DO NOWAIT
!$OMP END PARALLEL
```

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Benefit of DSL vs coding

The DSL Idea

$$\underline{\nabla_n}\psi(e) = \frac{\psi(c_1(e)) - \psi(c_0(e))}{\hat{l}}$$

```
grad_norm_psi_e =
      reduce( psi_c,
               CELL > EDGE,
               [1/lhat, -1/lhat]
             )
```

Open ACC

DSL compiler

```
!$ACC PARALLEL &
!$ACC PRESENT(ptr_patch, iidx, iblk, pci_c, grad_...)
!$ACC LOOP GANG
DO jb = i_startblk, i_endblk
 CALL get_indices_e(ptr_patch, ...)
 DO jk = slev, elev
   DO je = i_startidx, i_endidx
     grad_norm_psi_e(je,jk,jb) =  &
       ( psi_c(iidx(je,jb,2),jk,iblk(je,jb,2)) -
         psi_c(iidx(je,jb,1),jk,iblk(je,jb,1)) )
       / ptr_patch%edges%lhat(je,jb)
   ENDDO
 END DO
END DO
!$ACC END PARALLEL
!$ACC END DATA
```

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Benefit of DSL vs coding

The DSL Idea

$$\underline{\nabla_n}\psi(e) = \frac{\psi(c_1(e)) - \psi(c_0(e))}{\hat{l}}$$

```
grad_norm_psi_e =
      reduce( psi_c,
              CELL > EDGE,
              [1/lhat, -1/lhat]
           )
```

C++

DSL compiler

```
for(int k = 0 + 0; k < m_k_size; ++k) {
 for(auto const& loc : getEdges(LibTag{}, m_mesh)) {
   for(auto inner_loc :
     grad_norm_psi_e(loc, k + 0) = reduce(
         LibTag{}, m_mesh, loc, (::dawn::float_type)0.0,
         std::vector<dawn::LocationType>
         {dawn::Edges, dawn::Cells},
         [&](auto& lhs, auto red_loc1, auto const& weight)
         {
           lhs += weight *psi_c(red_loc1, k + 0);
          return lhs;
         },
         std::vector<::dawn::float_type>({-1.0 ,1.0});
   }
   grad_norm_psi_e(loc, k + 0) /= lhat_e(loc, k + 0)
 }
}
```

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Existing code & DSLs

Evolution rather than Revolution

- Although DSLs are very powerful, an application must be re-written in order to use them
- Applications in the weather/climate domain are large and under continuous development
- DSLs are relatively new and untested in this domain
    - Concerns over longevity of necessary tool chains
- To stop development on existing code and re-develop from scratch is expensive (time and effort)
- Community has a lot of skill and knowledge in existing coding approaches (Fortran)

Very attractive to be able to *translate* existing code into a DSL or use existing code in a DSL rather than re-write:

- Support science that cannot be specified in the DSL language
- Transition to high level DSLs by evolution not revolution
- Support code generation and translation

Need to regain lost information

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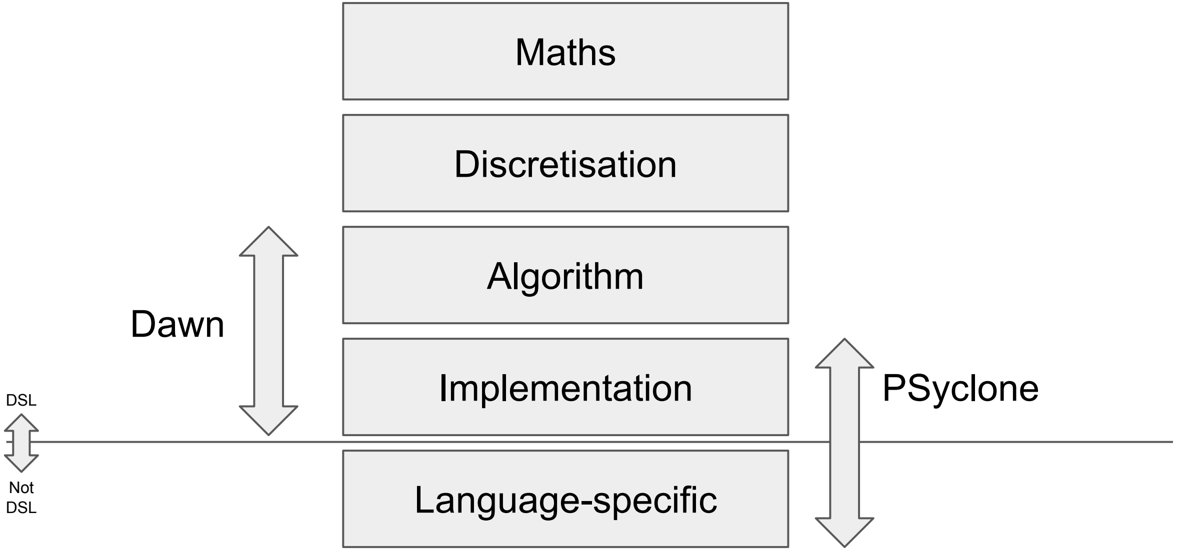
Levels of abstraction



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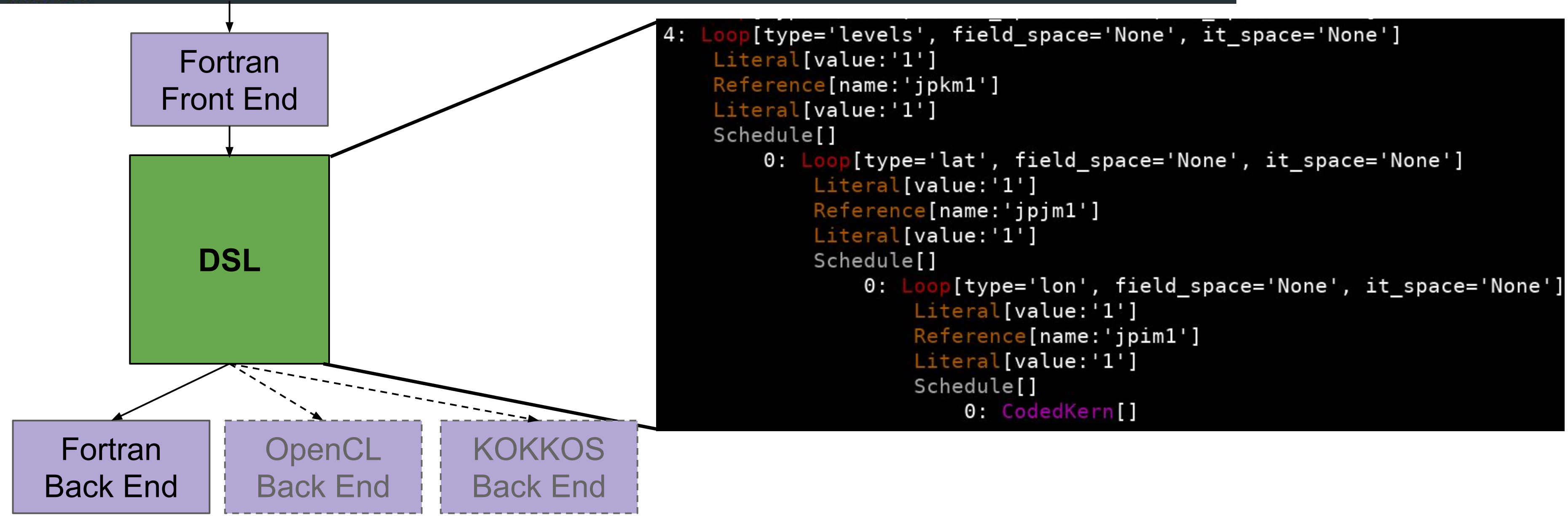
```fortran
! Horizontal tracer gradient
DO jk = 1, jpkm1
   DO jj = 1, jpjm1
      DO ji = 1, jpim1   ! vector opt.
         zdit(ji,jj,jk) = ( ptb(ji+1,jj  ,jk,jn) - ptb(ji,jj,jk,jn) ) * umask(ji,jj,jk)
         zdjt(ji,jj,jk) = ( ptb(ji  ,jj+1,jk,jn) - ptb(ji,jj,jk,jn) ) * vmask(ji,jj,jk)
      END DO
   END DO
END DO
```



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Summary

- Modelling required expertise in multiple disciplines (co-design)
- These disciplines work at different levels of abstraction
- Mixing science and performance can produce complex code
- Good to separate these concerns
- DSLs offer a way to do this
- DSLs support working at a high level of abstraction
- Higher level of abstraction allows a greater choice of implementation -> more performance
- Different DSLs can work at different levels of abstraction
- DSLs might support revolution and/or evolution

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Next

- Break
- Dawn intro
- PSyclone intro
- Tutorial

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