Introduction to DSLs
Simulation

- Levels
  - Maths
  - Discretisation
  - Algorithm
  - Implementation


**Abstract Description**

**Concrete Implementation**

Application scientist

Numericist

HPC expert
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

\[ \frac{\partial u}{\partial t} = \nu \nabla \cdot (\nabla u) - (u \cdot \nabla) u + F_{\text{body}} - \frac{1}{\rho} \nabla p \]

\[ \nabla \cdot u = 0 \]

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Maths level

\[ \text{grad} f = \nabla f \]

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
Algorithm level

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

Compare with calculus ...

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

\[ \nabla_n \psi(e) = \frac{\psi(c_1(e)) - \psi(c_0(e))}{\hat{l}} \]
Implementation level

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

\[
\nabla_n \psi(e) = \frac{\psi(c_1(e)) - \psi(c_0(e))}{\hat{l}}
\]

```fortran
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
```
Running fast/parallel

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

```plaintext
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
```
Running fast/parallel

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

```fortran
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
END DO
```
Running fast/parallel

- add directives to exploit multiple cores on shared memory machines
Running fast/parallel

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

\[ \nabla_{\mathbf{\hat{l}}} \psi(e) = \frac{\psi(c_1(e)) - \psi(c_0(e))}{\mathbf{\hat{l}}} \]

\#ifdef _OMP
!$OMP ....
#endif

\#else
!$ACC ....
#endif

DO jb = i_startblk, i_endblk
CALL get_indices_e(ptr_patch, ...)
\#ifdef __LOOP_EXCHANGE
DO je = i_startidx, i_endidx
\#else
DO jk = slev, elev
\#endif
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
!$OMP ...
#endif
\#else
!$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?

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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)
Domain Specific Languages

- DSL Frameworks are becoming a more and more viable approach for device-specific code generation, often achieving performance numbers unattainable 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)
Benefit of DSL vs coding

The DSL Idea

\[ \nabla_{\hat{\mu}} \psi(e) = \frac{\psi(c_1(e)) - \psi(c_0(e))}{\hat{l}} \]

DSL compiler

grad_norm.psi.e =
    reduce( psi_c,
        CELL > EDGE,
        [l/lhat, -l/lhat]
    )

OMP

!$OMP PARALLEL
!$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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The DSL Idea

\[ \nabla_{il} \psi(e) = \frac{\psi(c_1(e)) - \psi(c_0(e))}{\hat{l}} \]

\[
\text{grad\_norm\_psi\_e} = \text{reduce}\{ \text{psi\_c,}

\text{CELL > EDGE,}

[1/l\hat{\text{hat}}, -1/l\hat{\text{hat}}]

\}
\]

DSL compiler

Open ACC

!$ACC PARALLEL &
!$ACC PRESENT(ptr_patch, idx, blk, c_i, grad...)
!$ACC LOOP GANG
DO jb = i_startblk, i_endblk
CALL get_indices_e(ptr_patch, ...)
DO jk = slev, elev
DO je = i_startidx, i_endidx
grad\_norm\_psi\_e(je,jk,jb) = &
\text{(psi\_c(idx(je,jb,2),jk,blk(je,jb,2)) - psi\_c(idx(je,jb,2),jk,blk(je,jb,1)))}
/ ptr\_patch\%\text{edges}\%\hat{\text{lhat}}(je,jb)
ENDDO
END DO
END DO
!$ACC END PARALLEL
!$ACC END DATA

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Benefit of DSL vs coding

The DSL Idea

\[
\nabla_{n_1} \psi(e) = \frac{\psi(c_1(e)) - \psi(c_0(e))}{\hat{l}}
\]

grad_norm_psi_e =

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

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)
    }
}
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

- Maths
- Discretisation
- Algorithm
- Implementation
- Language-specific

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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