# A New Computational Design for a Global Icosahedral Model

***ECMWF: Use of HPC in Meteorology***

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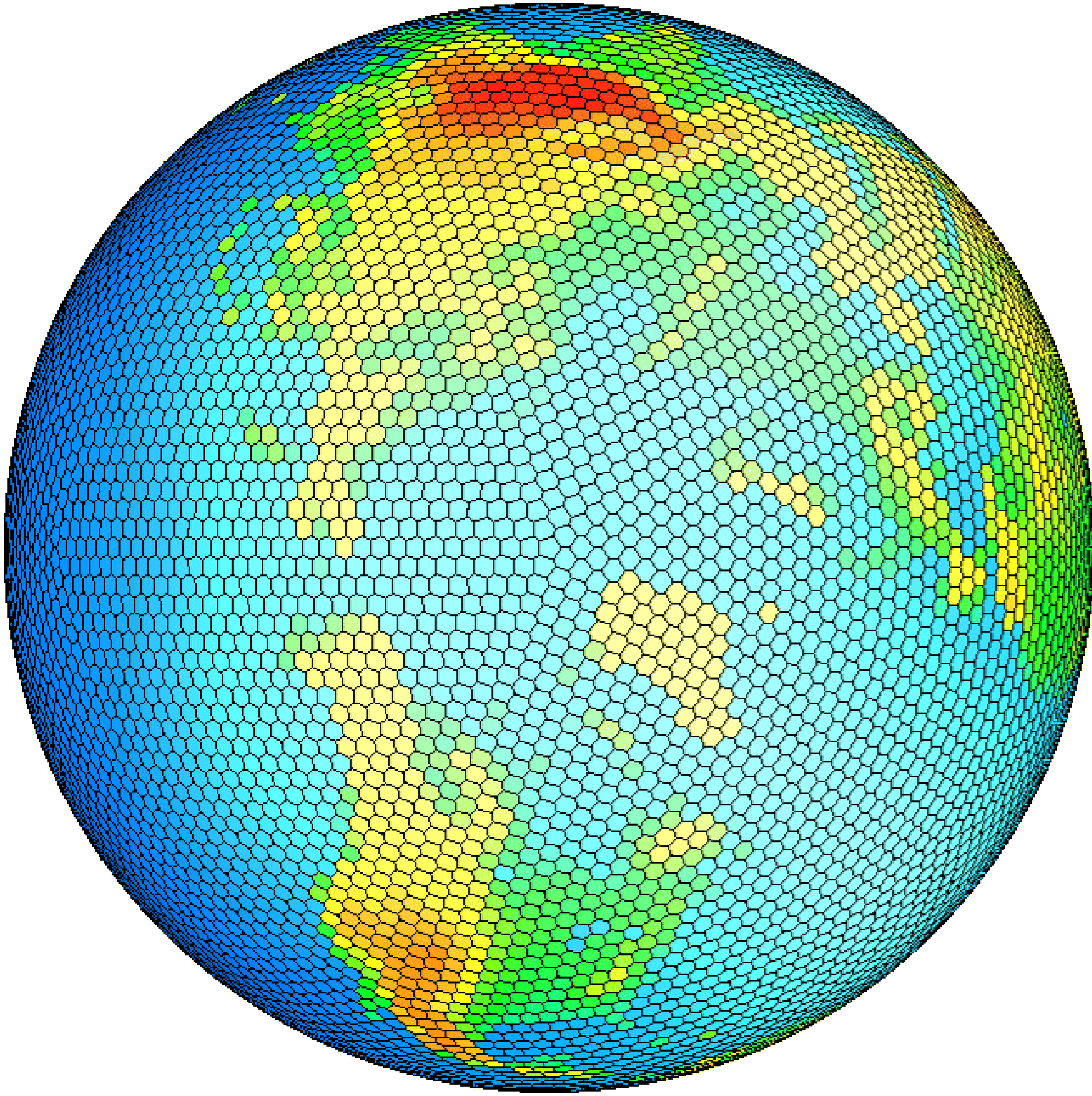

# Talk Summary

* NOAA's new ***Earth System Research Lab***

1. FIM Model Description

2. Computational Design

3. Some initial model results

Questions?

# Earth System Research Laboratory

**Mission:** To observe and understand the Earth system and to develop products through a commitment to research that will advance NOAA's environmental information and service on global-to-local scales.

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# NOAA/ESRL

## Flow-following-finite-volume

## Icosahedral

## Model

## FIM


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Rainer Bleck

Stan Benjamin

Sandy MacDonald

Jian-Wen Bao

Jaques Middlecoff



***Earth System Research Laboratory***

# Why Icosahedral Finite-Volume (FV) model ?

1) Icosahedral + FV approach provides conservation.
2) Icos quasi-uniform grid is free of pole problems.
3) Legendre polynomials become inefficient at high resol.
4) Spectral models require global communication which is inefficient on MPP with distributed memory.
5) Spectral models tend to generate noisy tracer transport.

Since Icosahedral models are based on a local numerical scheme, they are free of above problems 3 – 5.

# Flow-following, finite volume Icosahedral Model (FIM)

Icosahedral grid, with spring dynamics implementation

Finite volume, flux form equations in horizontal (planned - Piecewise Parabolic Method)

Hybrid isentropic-sigma ALE vertical coordinate (arbitrary Lagrangian-Eulerian), target PPM

Hydrostatic (extension to non-hydrostatic later)

GFS physics, Scalable Modeling System parallelization

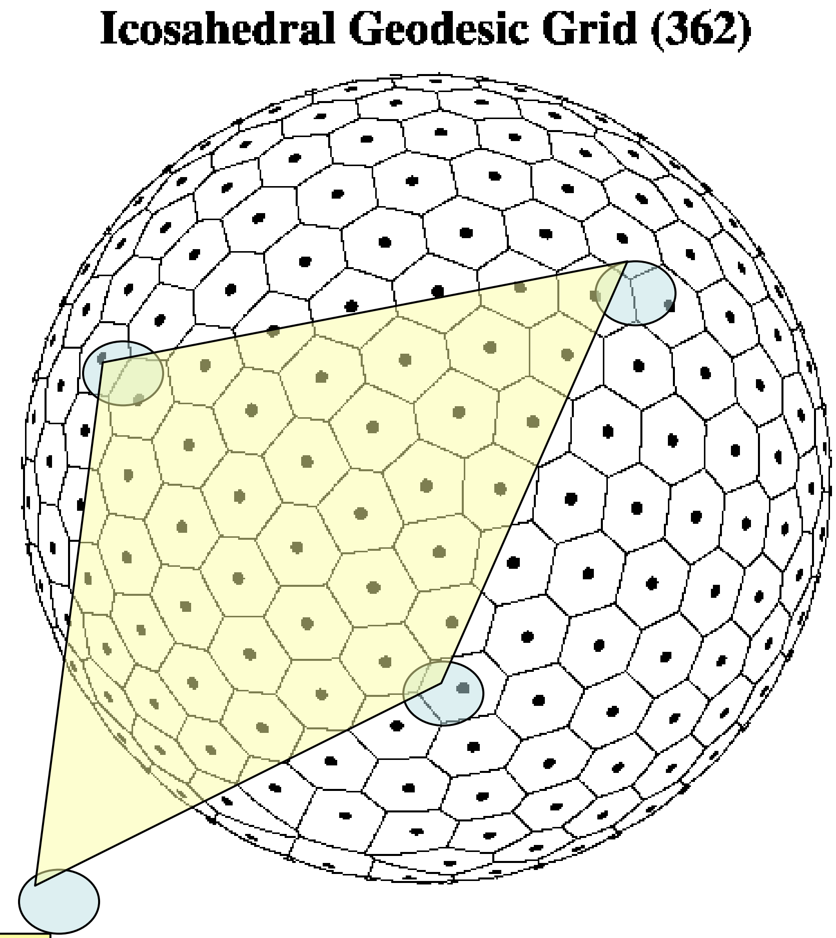
Earth System Modeling Framework

**Computational design: All calculations local using remap and interpolation polynomial. Model 1D grid can is table driven and can be in any order, allowing highly efficient empirical matching to parallel computer configuration.**

# FIM Model

6 rhombuses
12 pentagons
Others hexagons

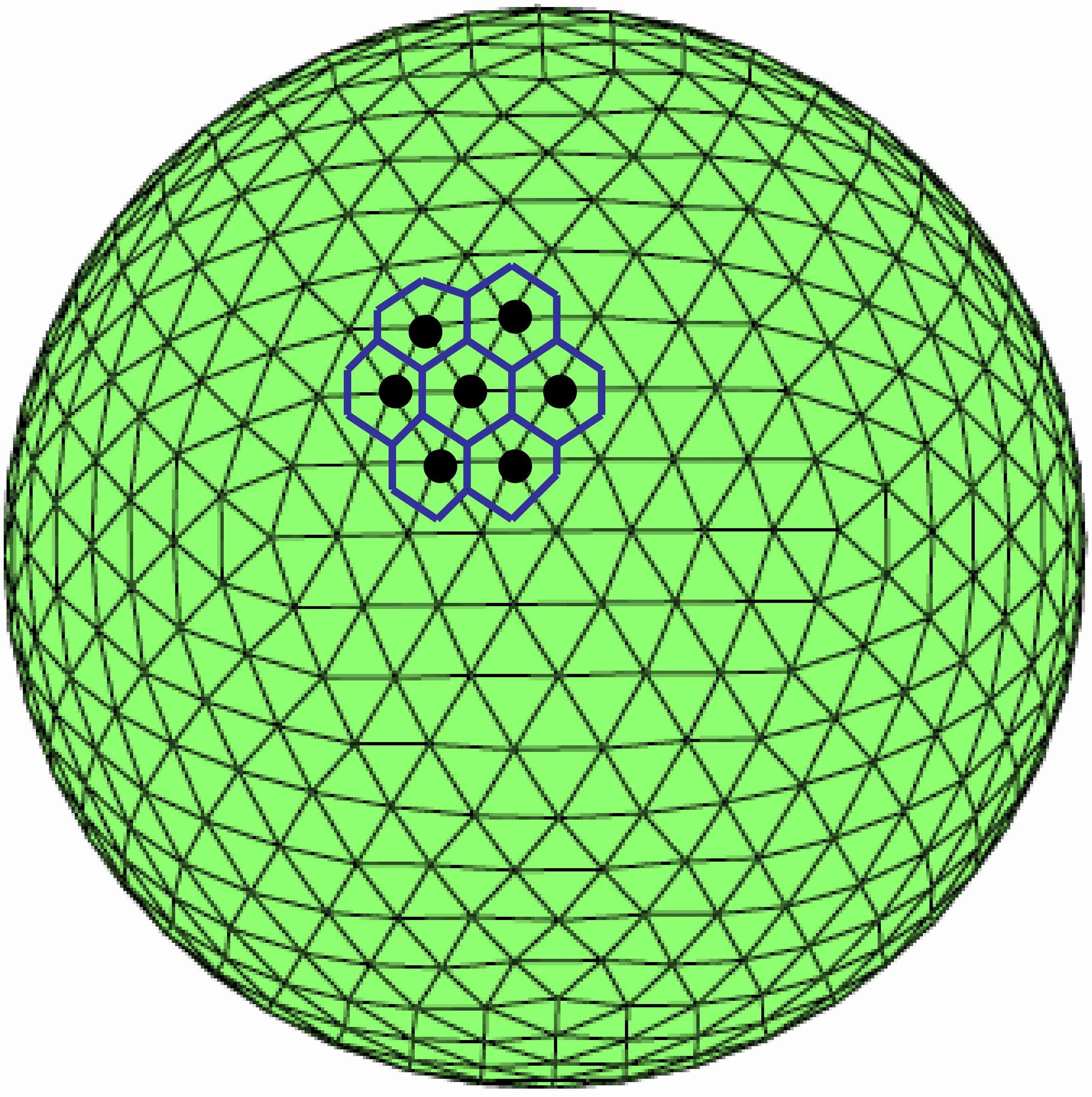
Ratio of map-scale factor
From max-min – 0.95
(for level-5 icosahedral
grid – 240km resolution)



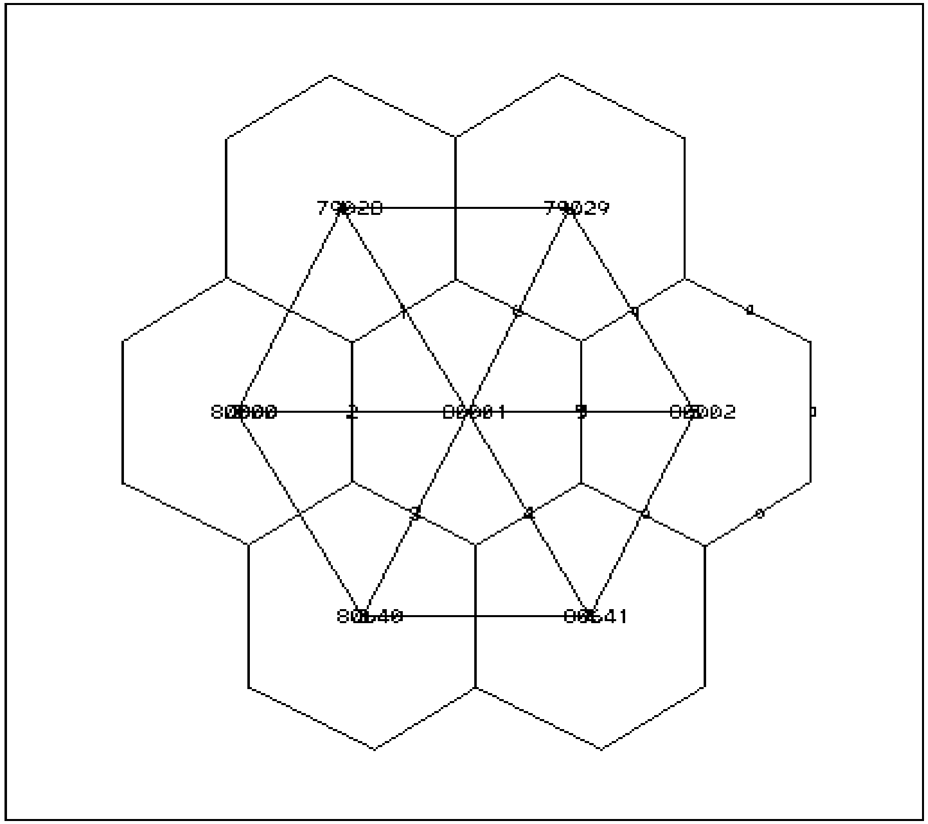

((2**n)**2)*10 + 2 = no. cells

5th level -
(32**2)*10 + 2 = 10242 ~240km resolution
6th level – 40962 cells ~120km resolution
7th level – 163842 cells ~60km resolution
8th level – 655,362 cells ~30km resolution
9th level – 2,621,442 cells ~15km resolution

**Goal: Daily two week weather prediction at 15 km horizontal, ~ 100 levels vertical by end of 2007.**



# Horizontal Grid Structure



Finite volume application

- flux into each from from surrounding donor cells
- S.-J. Lin formulation for lat/lon global model, successfully adapted to icosahedral grid by Lee and MacDonald in collaboration with Lin

$$
\begin{cases}
u_t - \eta v + \left( \dot{s} \dfrac{\partial p}{\partial s} \right) \dfrac{\partial u}{\partial p} = -m \dfrac{\partial (M+E)}{\partial x} + m\Pi \dfrac{\partial \theta}{\partial x} \\
v_t + \eta u + \left( \dot{s} \dfrac{\partial p}{\partial s} \right) \dfrac{\partial v}{\partial p} = -m \dfrac{\partial (M+E)}{\partial y} + m\Pi \dfrac{\partial \theta}{\partial y} \\
\left( \dfrac{\partial p}{\partial s} \right)_t + m^2 \nabla_s \cdot \left( \dfrac{\vec{V}_h}{m} \dfrac{\partial p}{\partial s} \right) + \dfrac{\partial}{\partial s} \left( \dot{s} \dfrac{\partial p}{\partial s} \right) = 0 \\
\left( \theta \dfrac{\partial p}{\partial s} \right)_t + m^2 \nabla_s \cdot \left[ \left( \dfrac{\vec{V}_h}{m} \dfrac{\partial p}{\partial s} \right) \theta \right] + \dfrac{\partial}{\partial s} \left[ \left( \dot{s} \dfrac{\partial p}{\partial s} \right) \theta \right] = \dfrac{\partial p}{\partial s} \dfrac{\dot{H}}{C_p T} \\
\dfrac{\partial M}{\partial \theta} = \Pi \qquad \textit{where} \quad \Pi = c_p (p / p_0)^{R/c_p}
\end{cases}
$$

$$
\left( q \frac{\partial p}{\partial s} \right)_t + m^2 \nabla_s \cdot \left[ \left( \frac{\vec{V}_h}{m} \frac{\partial p}{\partial s} \right) q \right] + \frac{\partial}{\partial s} \left[ \left( \dot{s} \frac{\partial p}{\partial s} \right) q \right] = \textit{Source}
$$

# Numerics of the FIM

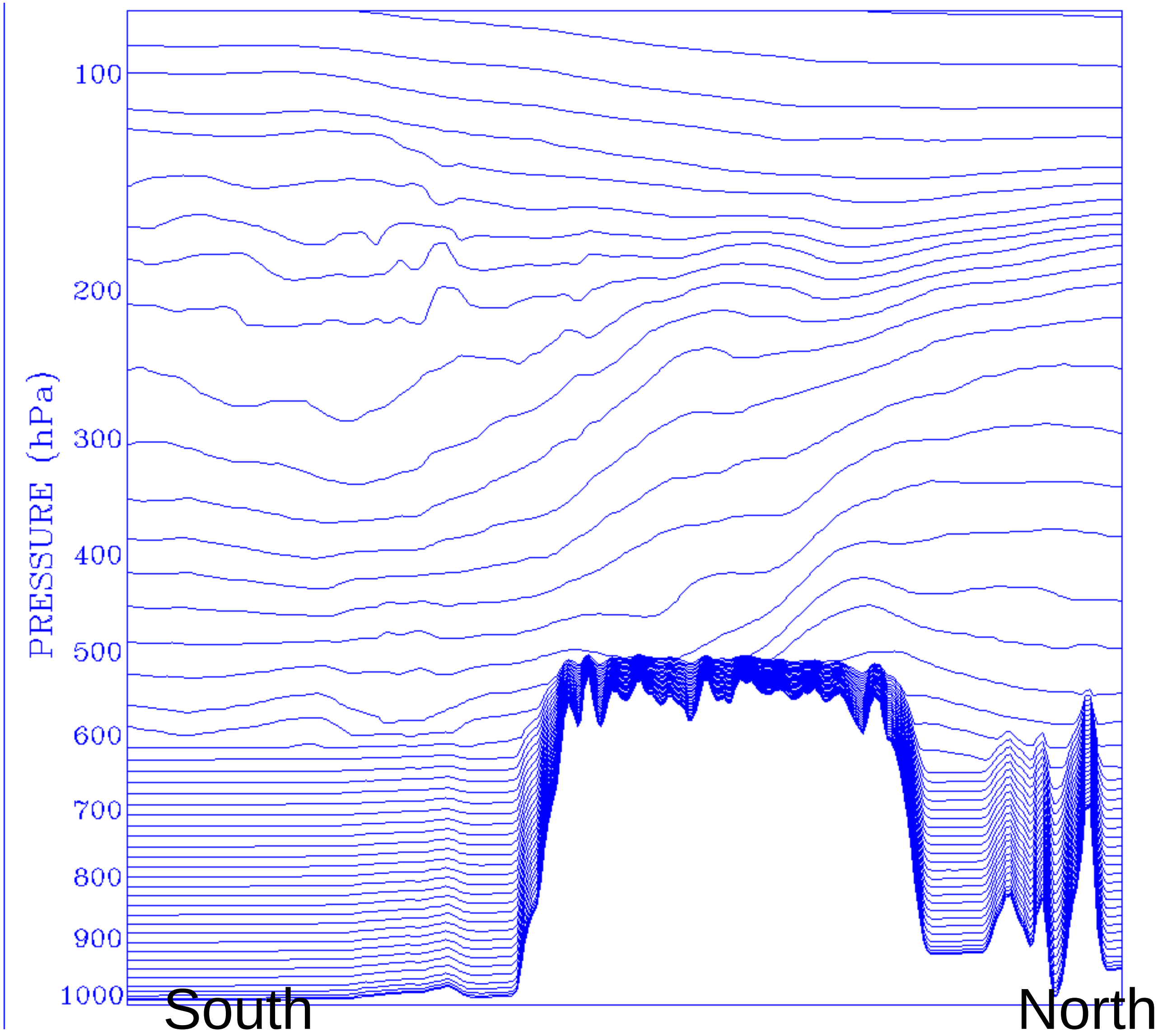
- Finite-Volume operators including
  (i) Vorticity operator based on Stoke theorem,
  (ii) Divergence operator based on Gauss theorem,
  (iii) Gradient operator based on Green's theorem.

- Each Icosahedral cell is solved on a local coordinate.

- Model variables are defined on a non-staggered A-grid.

- Explicit 3$^{rd}$-order Adams-Bashforth time differencing.

- Monotonicity and positive definite based on Zalesek (1979) Flux Corrected Transport.




# Vertical Coordinate over Himalayas

Design:
Rainer Bleck

Data interpolated to current RUC coordinate using Asia terrain field -13km dx

Adjustments planned

- Relaxed sigma layer compression up to 400 hPa
- Reference $\theta_v$ levels down to 200 K (currently 232K in RUC)

# Implementation of GFS physics

1. The first-order non-local turbulence and surface-layer scheme

2. The 4-layer Noah soil model with Zobler soil type

3. The simple cloud scheme plus simplified Arakawa-Schubert convective scheme

4. The Chou SW, RRTM LW schemes interacting with diagnosed cloud water and RH clouds

   (Using the GFS initial condition and static fields including Reynolds SST , NESDIS snow cover, USAF snow depth, NESDIS ice analysis , GCIP vegetation type, NESDIS vegetation fraction)

**FIM Project done in cooperation with NCEP EMC**

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# Computational Design

(MacDonald)

1. One dimensional, single loop code.

2. Table driven (can be in any order).

3. Local remap to 2D general stereo grid.

4. Interpolation polynomial (Van Der Monde) used for calculations.

5.  ESMF compliant.

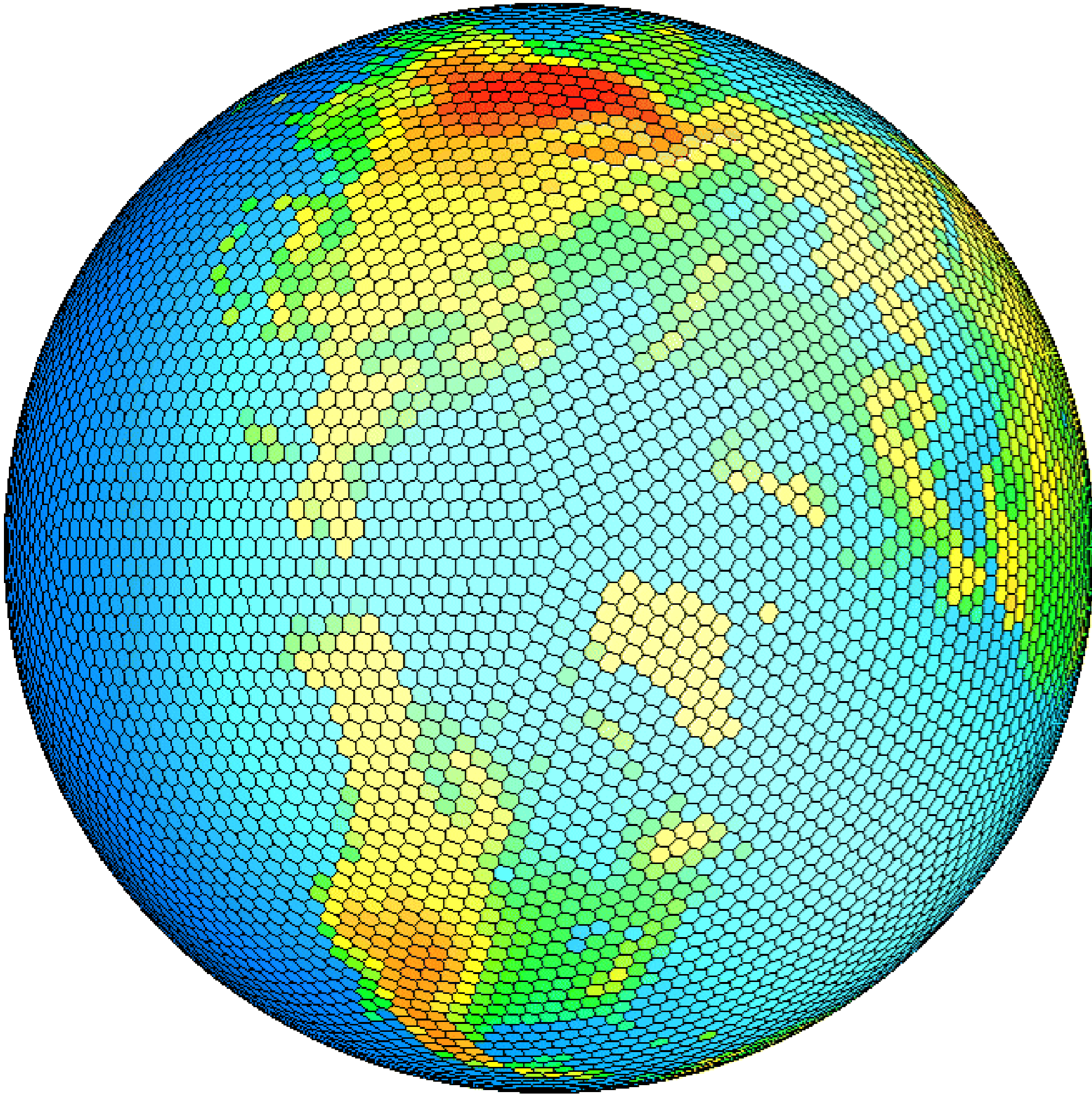
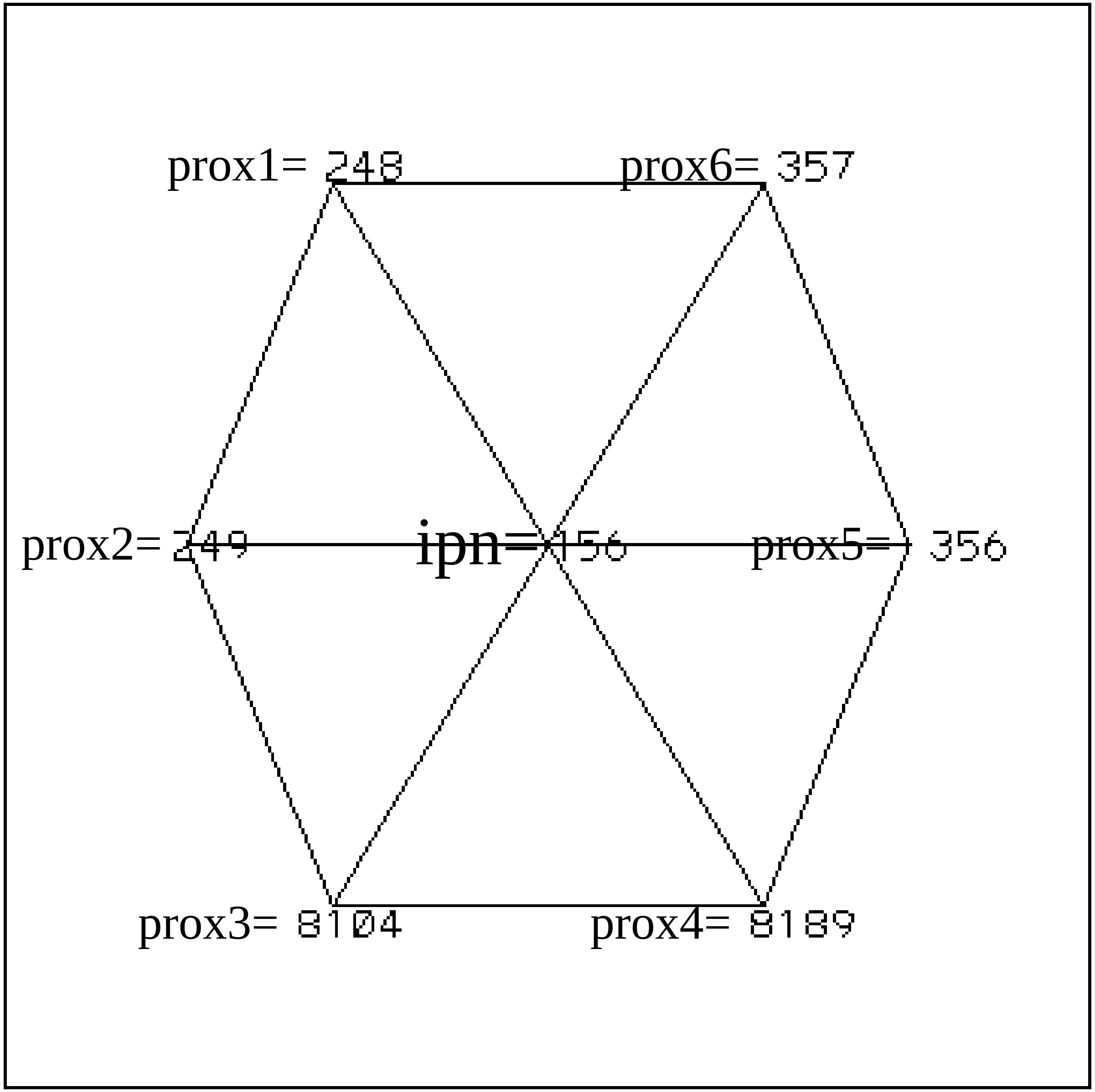


Figure from D. Randall

| Memory Loc | Lat/Lon | Proximity Pts | H or P |
|---|---|---|---|
| 1 | ⋮ | ⋮ | ⋮ |
| 2 | | | |
| ⋮ | | | |
| 30 | 32.5 / 10.0 | 9090, 9122, 31, 62, 61, 29 | H |
| 31 | 30.5 / 10.0 | 30, 9122, 9154, 32, 63, 62 | H |
| 32 | 28.5 / 10.0 | 31, 9154, 9186, 33, 64, 63 | H |
| 33 | 26.5 / 10.0 | 9186, 9218, 65, 64, 32 | P |
| 34 | 86.8 / 46.0 | 2, 3, 35, 66, 2051, 2050 | H |
| 35 | 85.0 / 32.4 | 3, 4, 36, 67, 66, 34 | H |
| 36 | 83.2 / 26.0 | 4, 5, 37, 68. 67, 35 | H |
| 37 | 81.2 / 22.5 | 5, 6, 38, 69, 68, 36 | H |
| 38 | 79.3 / 20.2 | 6, 7. 39, 70, 69, 37 | H |
| ⋮ | ⋮ | ⋮ | ⋮ |


prox1= 248
prox6= 357
prox2= 249
ipn= 156
prox5= 356
prox3= 8104
prox4= 8189

# Space Filling Curve: Hilbert curve (N=2**n)

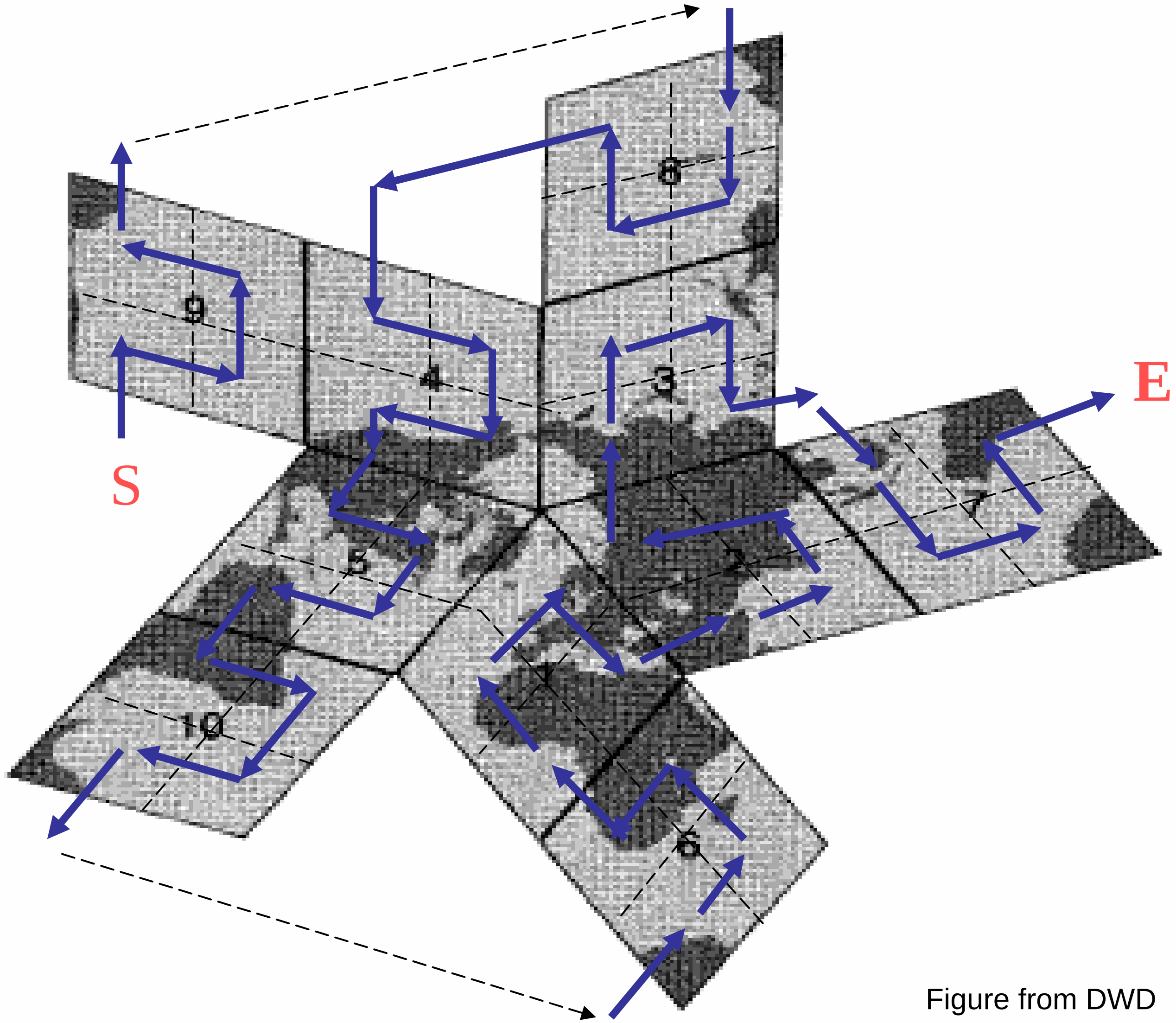
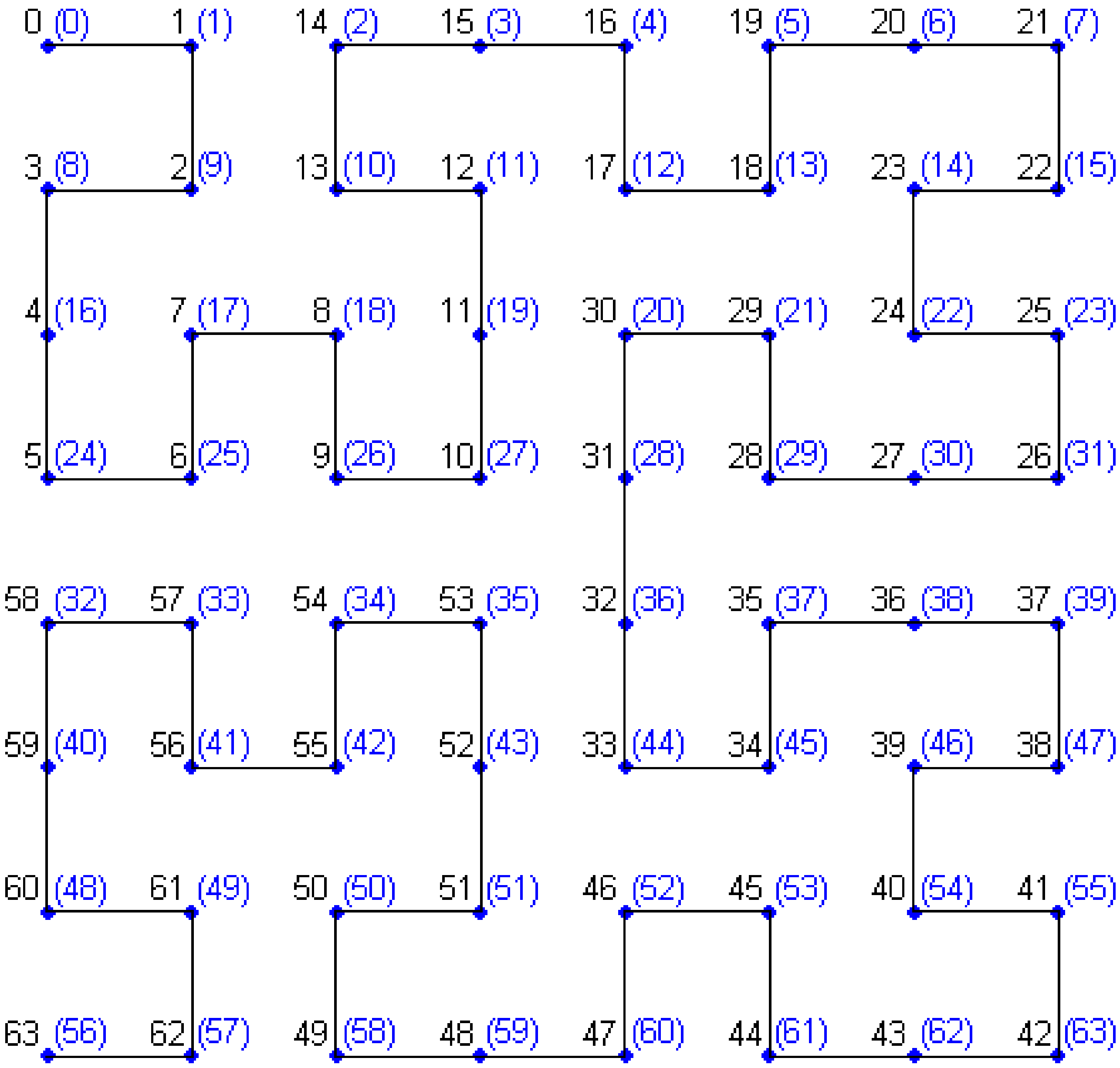
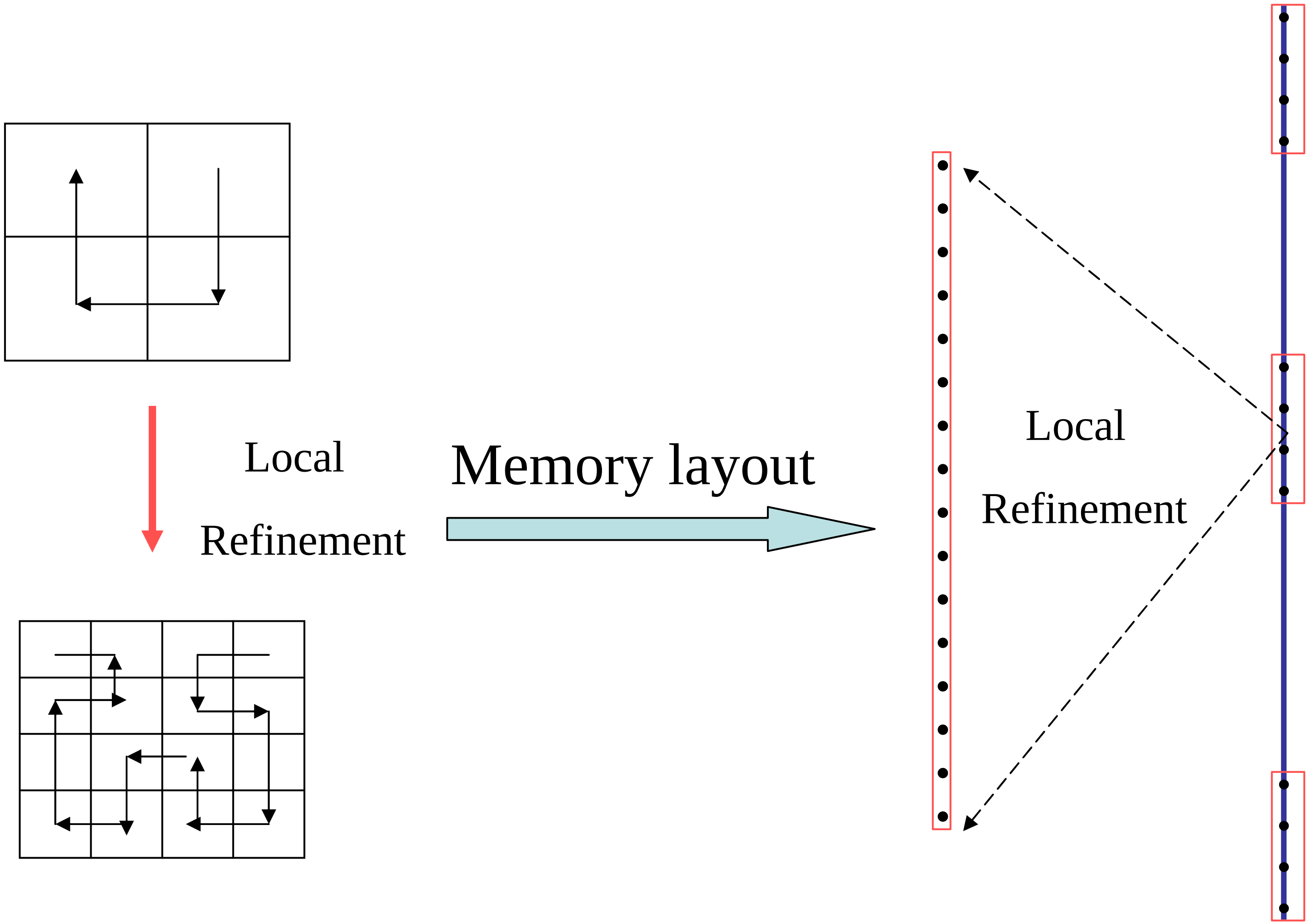



Figure from DWD


0 (0) 1 (1) 14 (2) 15 (3) 16 (4) 19 (5) 20 (6) 21 (7)
3 (8) 2 (9) 13 (10) 12 (11) 17 (12) 18 (13) 23 (14) 22 (15)
4 (16) 7 (17) 8 (18) 11 (19) 30 (20) 29 (21) 24 (22) 25 (23)
5 (24) 6 (25) 9 (26) 10 (27) 31 (28) 28 (29) 27 (30) 26 (31)
58 (32) 57 (33) 54 (34) 53 (35) 32 (36) 35 (37) 36 (38) 37 (39)
59 (40) 56 (41) 55 (42) 52 (43) 33 (44) 34 (45) 39 (46) 38 (47)
60 (48) 61 (49) 50 (50) 51 (51) 46 (52) 45 (53) 40 (54) 41 (55)
63 (56) 62 (57) 49 (58) 48 (59) 47 (60) 44 (61) 43 (62) 42 (63)

# Memory is laid out to maximize efficiency:



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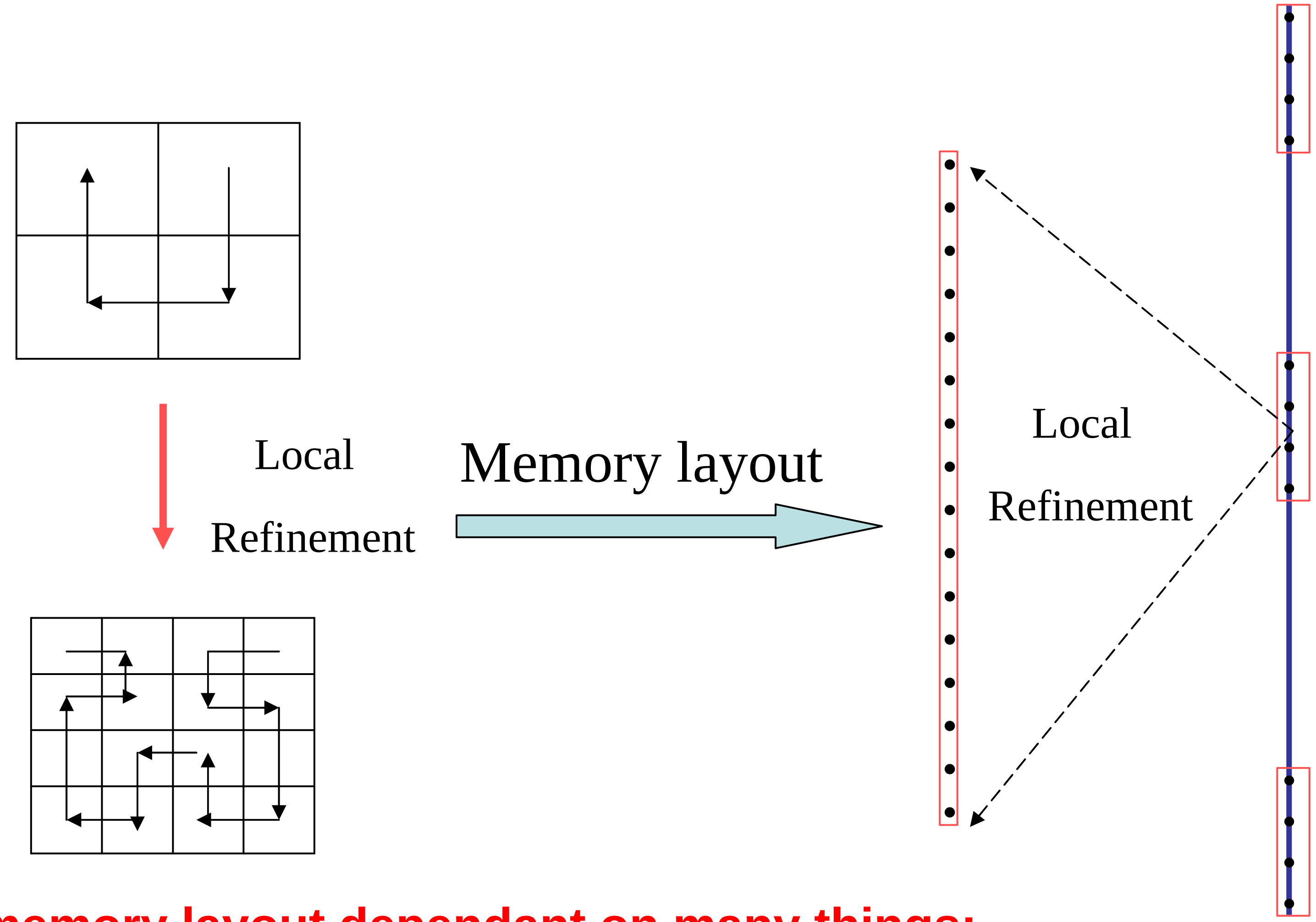
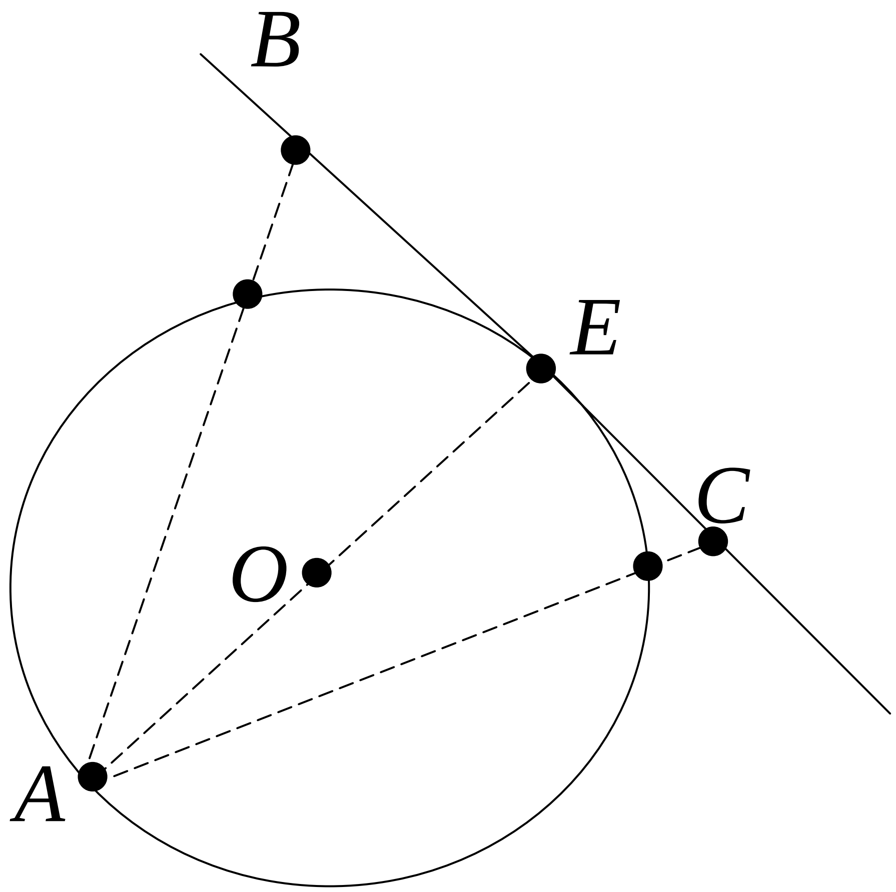
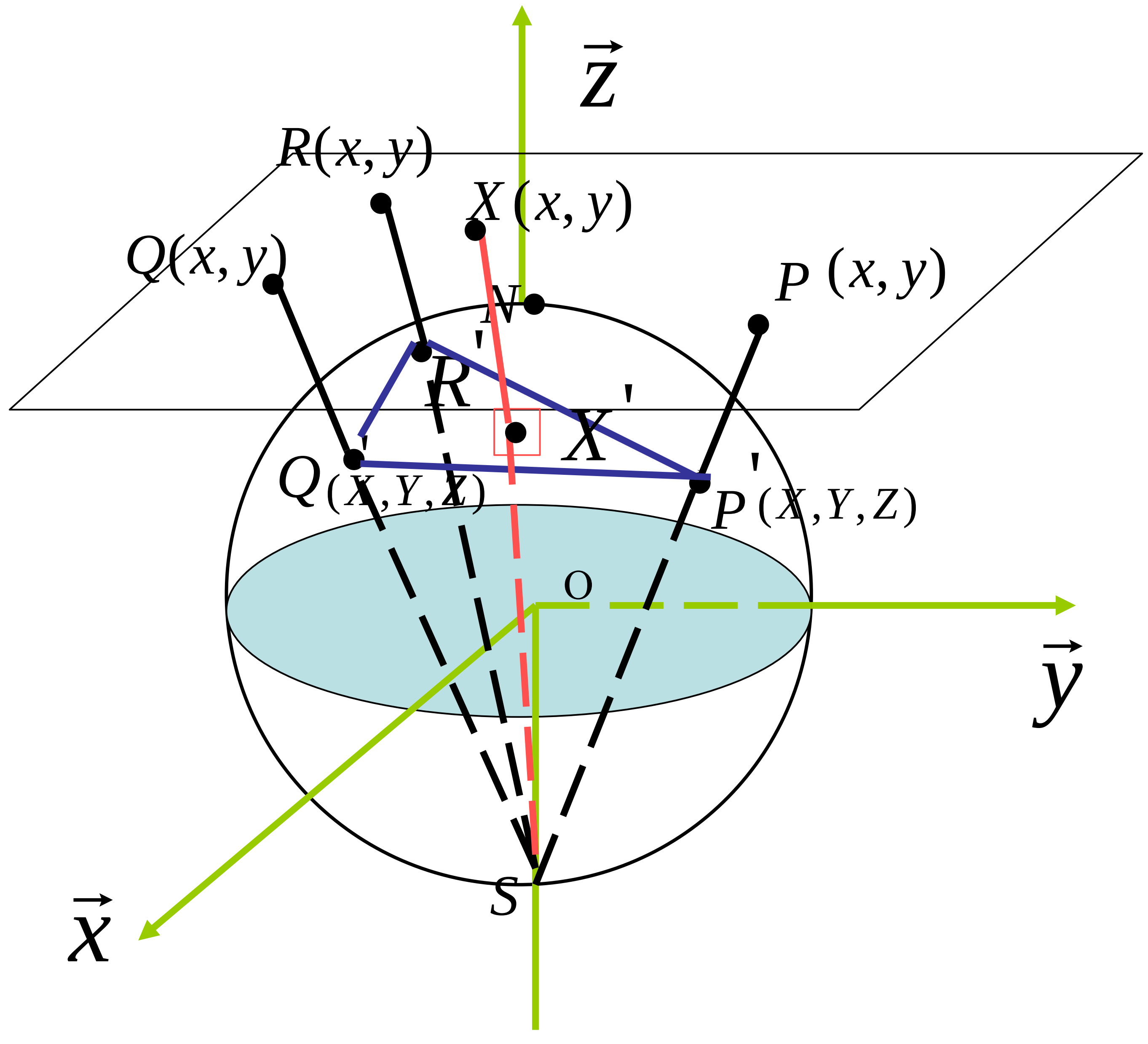



**Best memory layout dependant on many things:**

**Processor types, cache configuration, number of proc etc.**

# General Stereographic Projection





$\vec{z}$
R(x, y)
X (x, y)
Q(x, y)
P (x, y)
N
R'
X'
Q'(X,Y,Z)
P'(X,Y,Z)
O
$\vec{y}$
S
$\vec{x}$

Polynomial interpolation of $(n+1)$ points means that

$$f(x) = a_0 + a_1 x + a_2 x^2 + \ldots\ldots + a_{n-1} x^{n-1} + a_n x^n$$

It can be written in a matrix - vector form as follow :

$$\underbrace{\begin{bmatrix} 1 & x_1 & x_1^2 & \cdots & \cdots & x_1^{n-1} & x_1^n \\ 1 & x_2 & x_2^2 & \cdots & \cdots & x_2^{n-1} & x_2^n \\ 1 & x_3 & x_3^2 & \cdots & \cdots & x_3^{n-1} & x_3^n \\ \vdots & \vdots & \vdots & \cdots & \cdots & \vdots & \vdots \\ \vdots & \vdots & \vdots & \cdots & \cdots & \vdots & \vdots \\ 1 & x_{n-1} & x_{n-1}^2 & \cdots & \cdots & x_{n-1}^{n-1} & x_{n-1}^n \\ 1 & x_n & x_n^2 & \cdots & \cdots & x_n^{n-1} & x_n^n \end{bmatrix}}_{\text{Vandermonde Matrix}} \begin{bmatrix} a_0 \\ a_1 \\ a_2 \\ \vdots \\ \vdots \\ a_{n-1} \\ a_n \end{bmatrix} = \begin{bmatrix} f_0 \\ f_1 \\ f_2 \\ \vdots \\ \vdots \\ f_{n-1} \\ f_n \end{bmatrix}$$

Williamson et. al. (1992) test cases of :

Case I: Advection of cosine bell over poles

Case II: Steady state nonlinear geostrophic flow

Case V:  Flow over an isolated mountain

Case VI: Rossby-Haurwitz solution

Baroclinic Case

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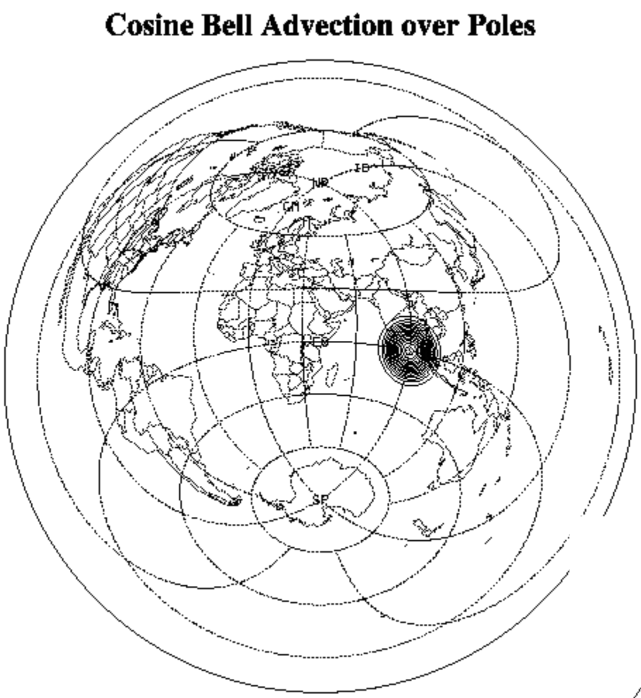
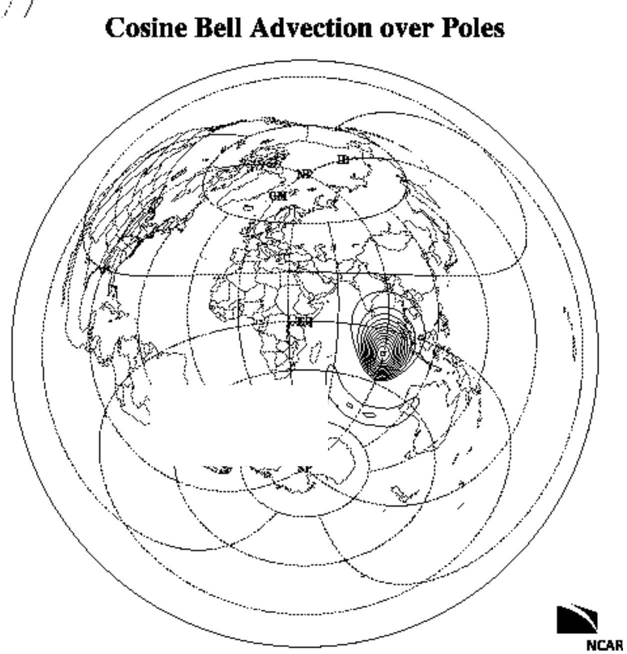
# Cosine bell advected over pole

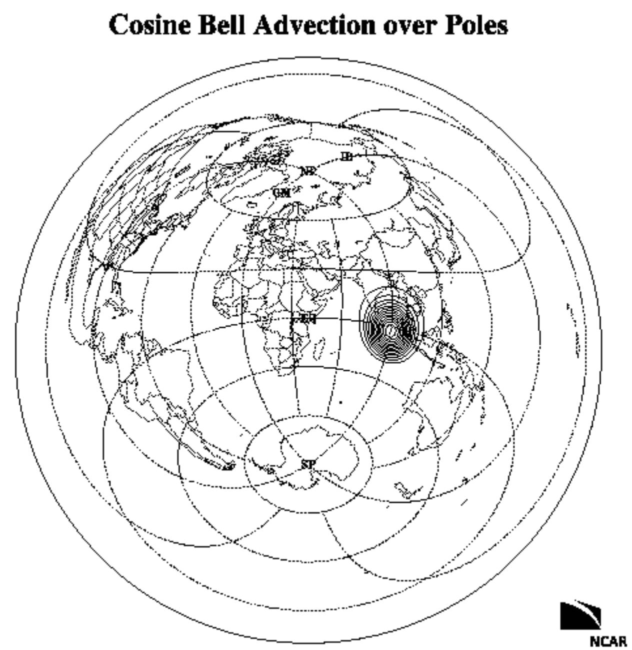



**Initial Field**

**Piecewise Constant**




**Piecewise Linear**



# Conclusion

A new computational design for a global model has been developed.

It may allow significant increases in efficiency by “tailoring” memory layout to the computational system.