Coupling Glimmer-CISM to POP using an Immersed Boundary Method

Xylar Asay-Davis
Bill Lipscomb, Steve Price
Los Alamos National Lab

CCSM Land Ice Working Group
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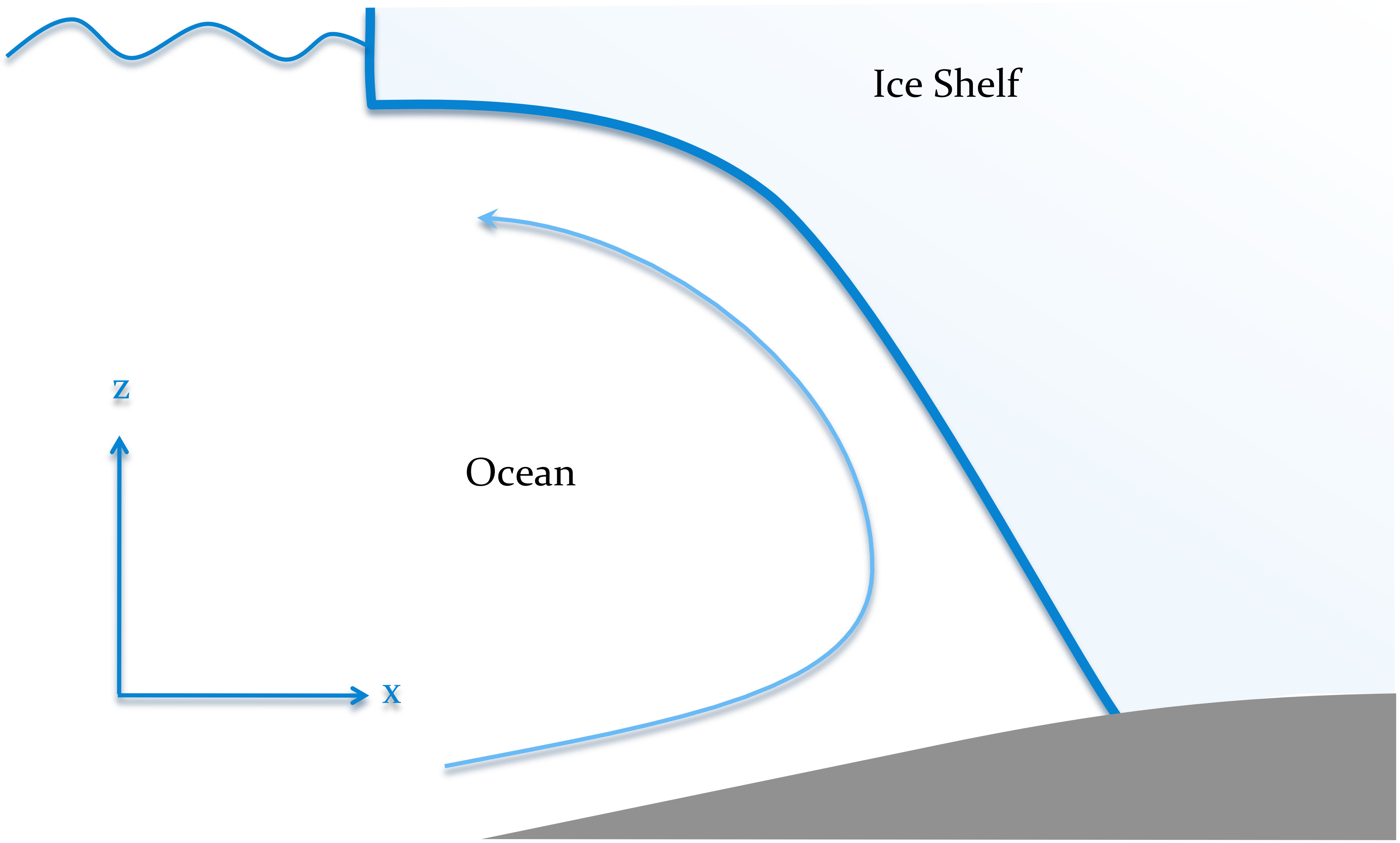
Outline

- What are Immersed Boundaries?
- How are Immersed Boundaries implemented?
- Boundary Conditions for Ice Shelves and Oceans

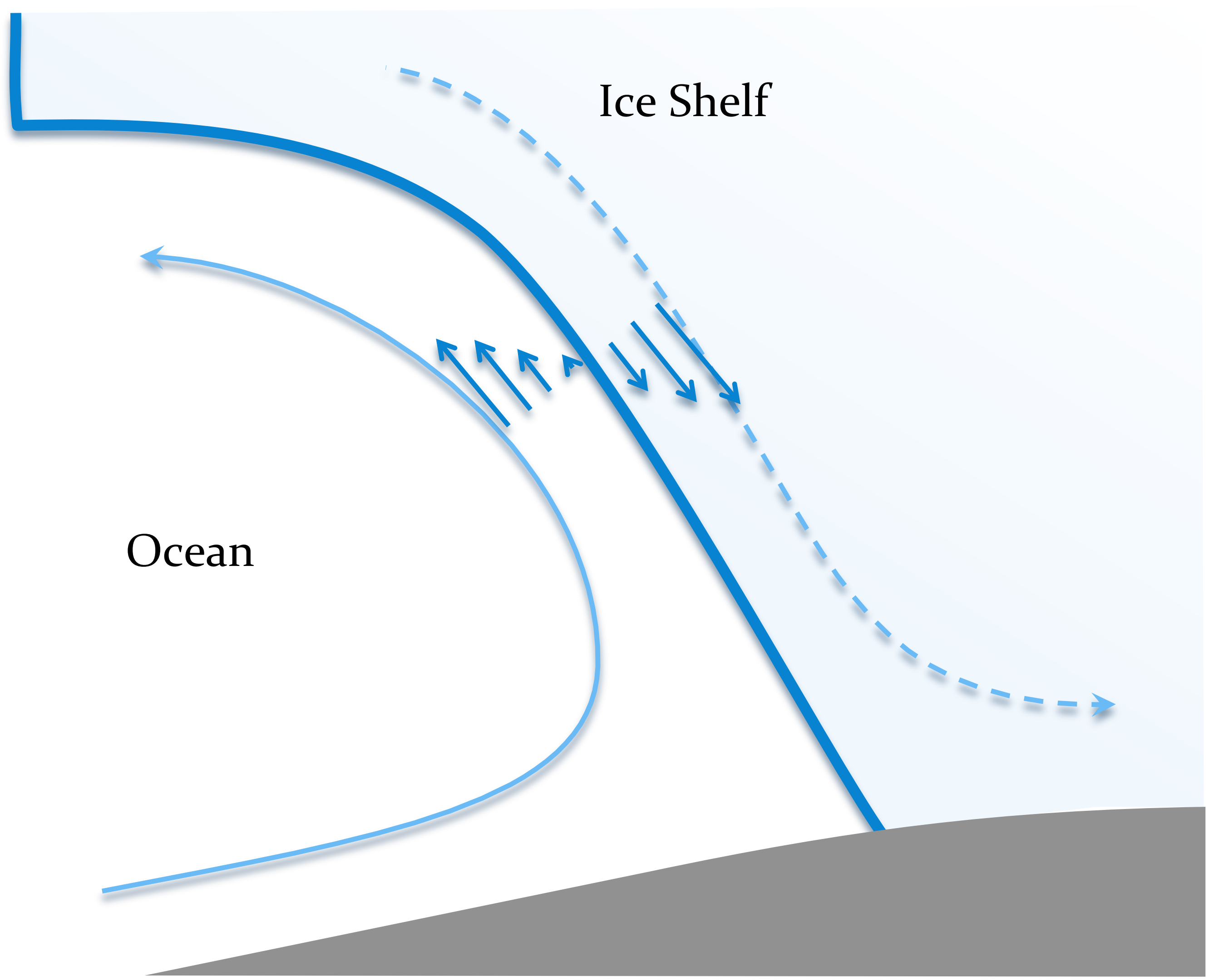
Some Previous Work

- Immersed Boundary Method (IBM) in ocean modeling:
  - Yu-Heng and Ferziger 2003
- IBM review article:
  - Mittal and Iaccarino 2005
- IBM and boundary layers, direct fluid forcing:
  - Choi et al. 2007
- IBM with image points:
  - Mittal et al. 2008

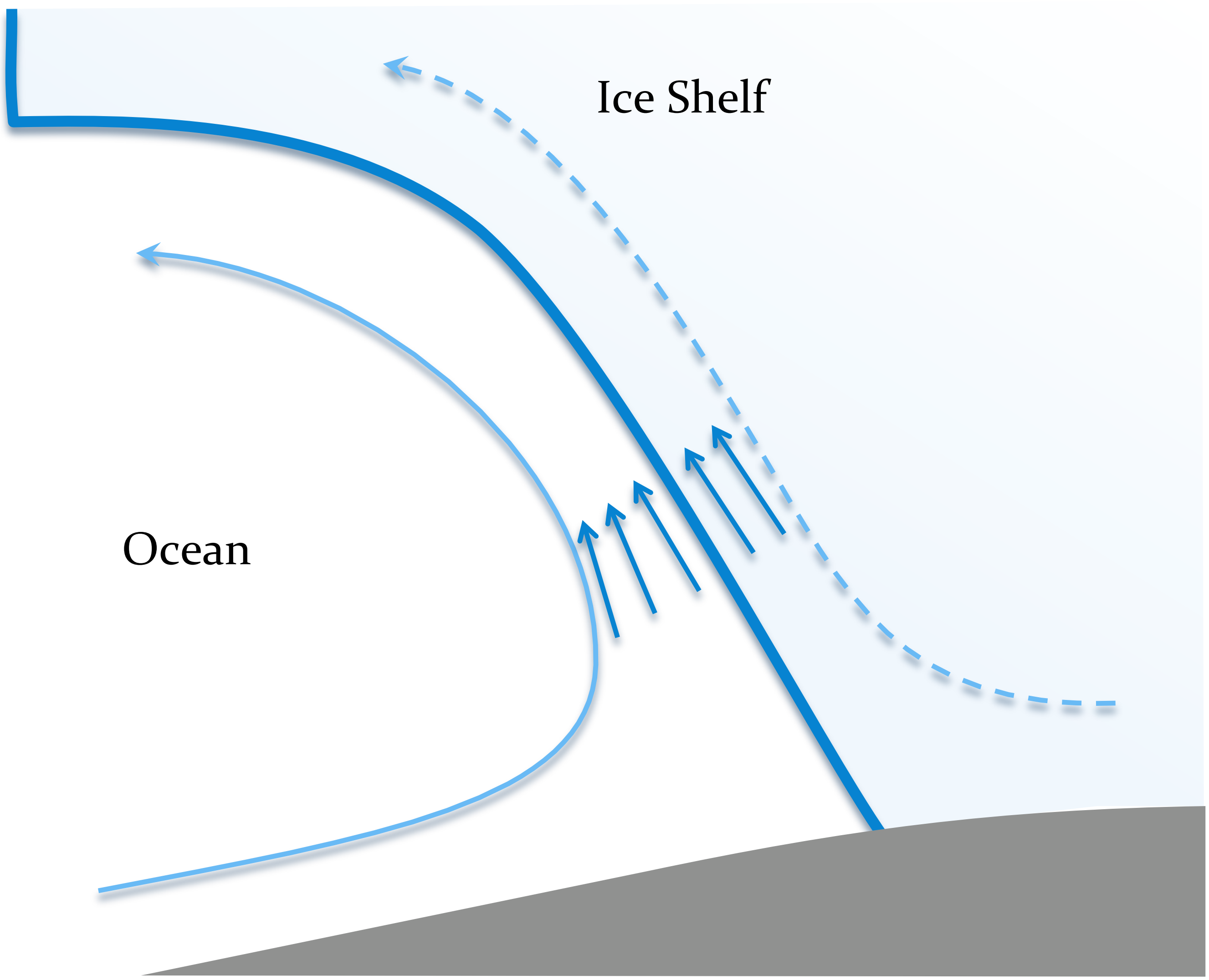
What are Immersed Boundaries?



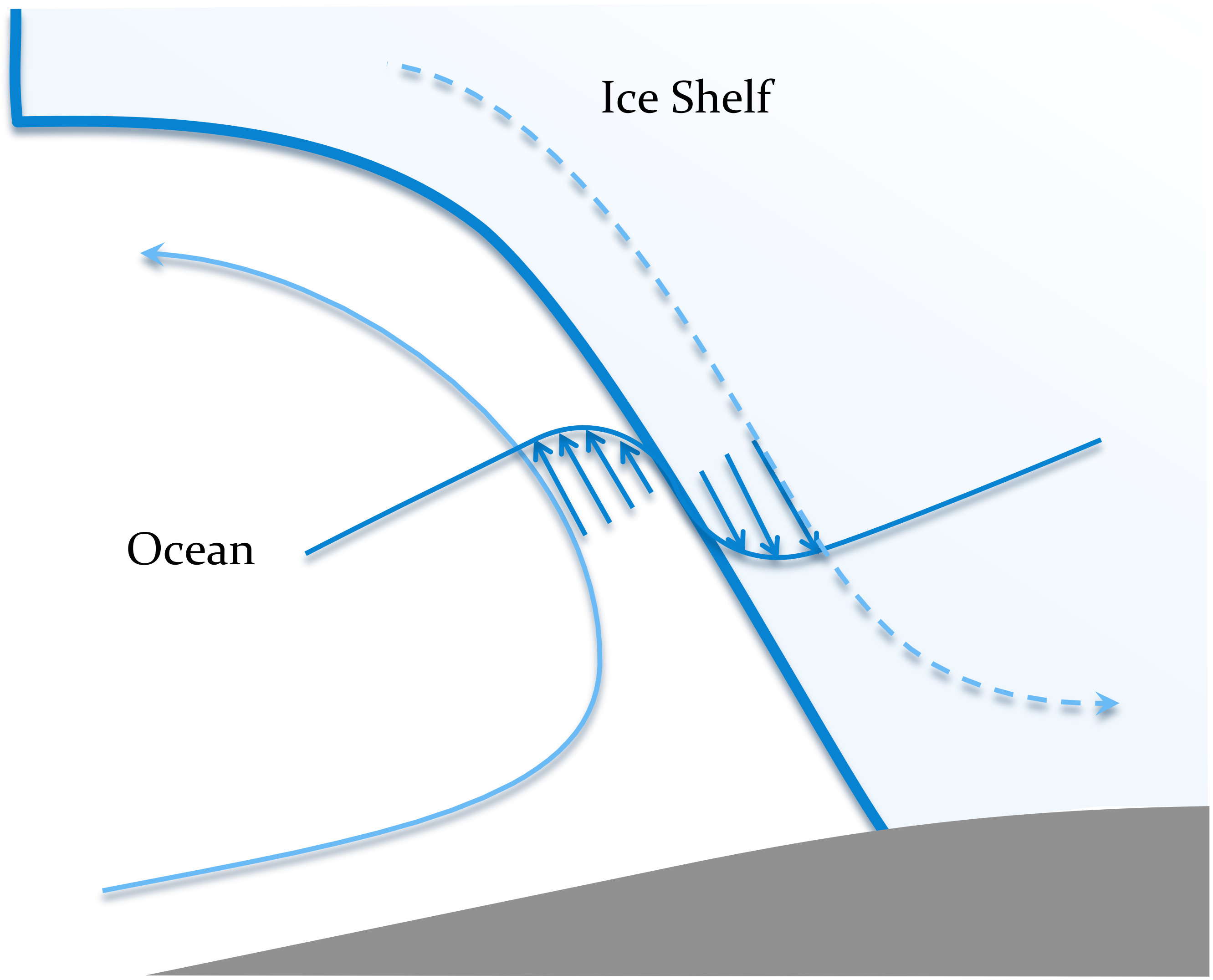
No Slip Boundary Condition



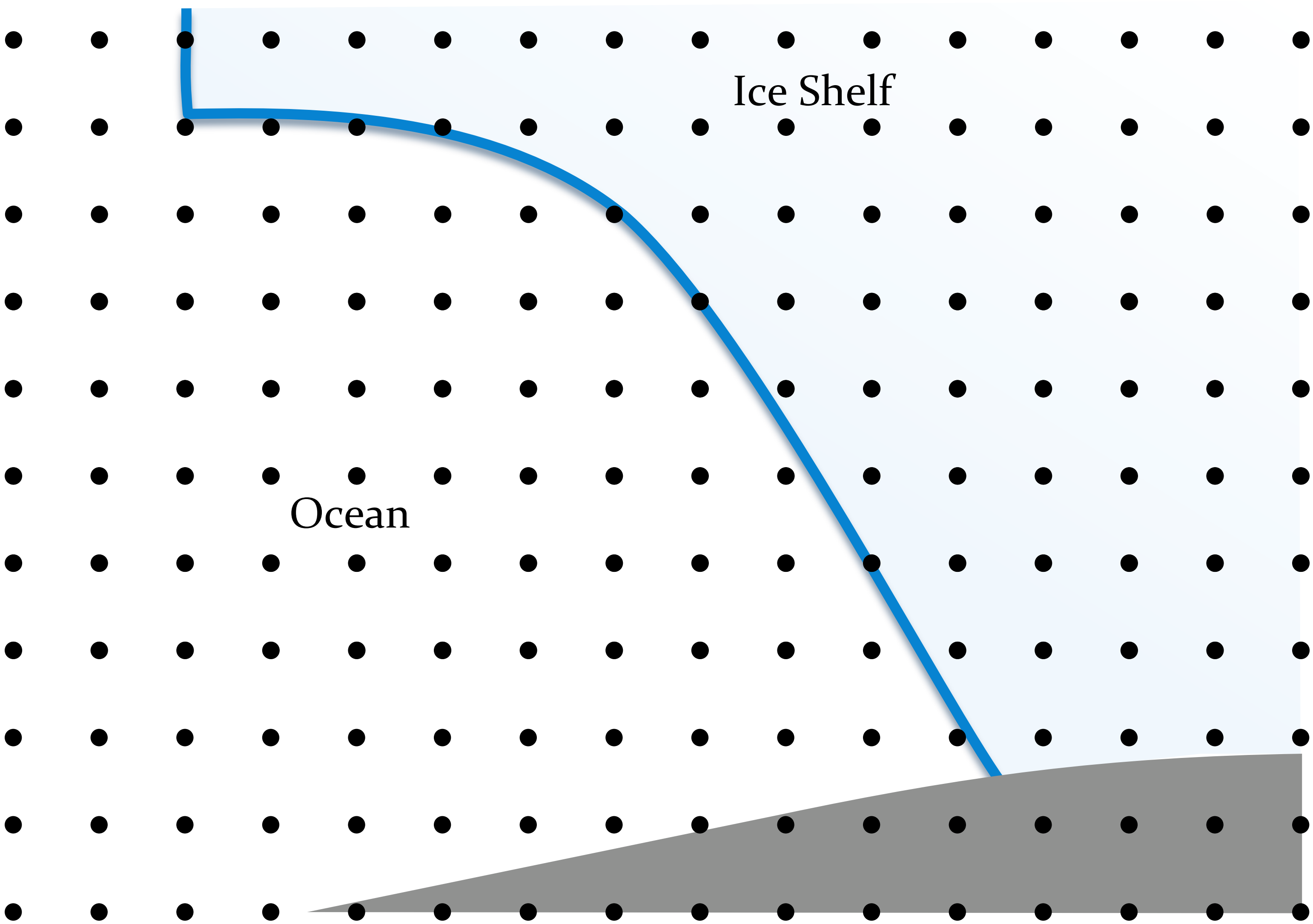
Free Slip Boundary Condition



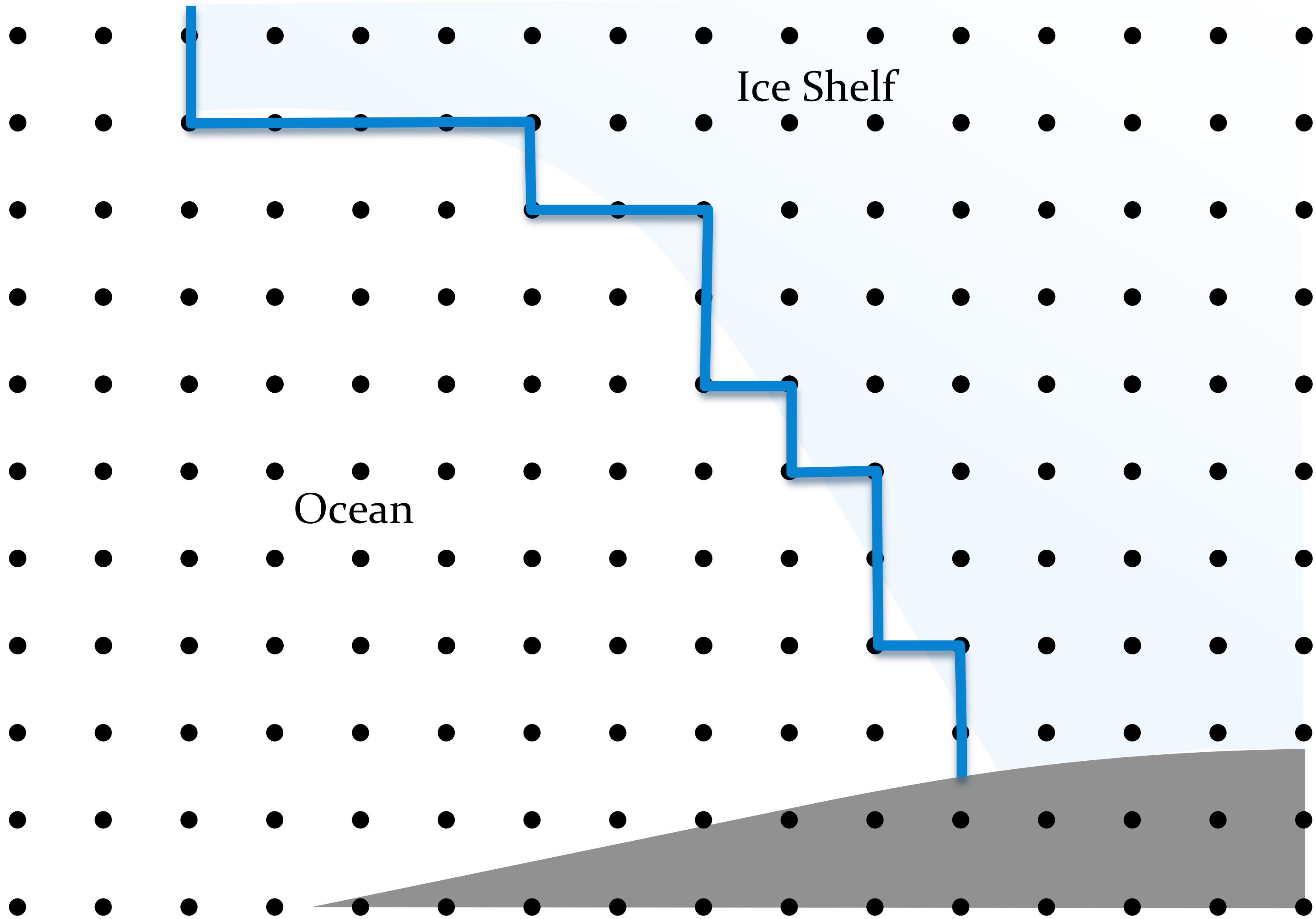
Boundary Layer



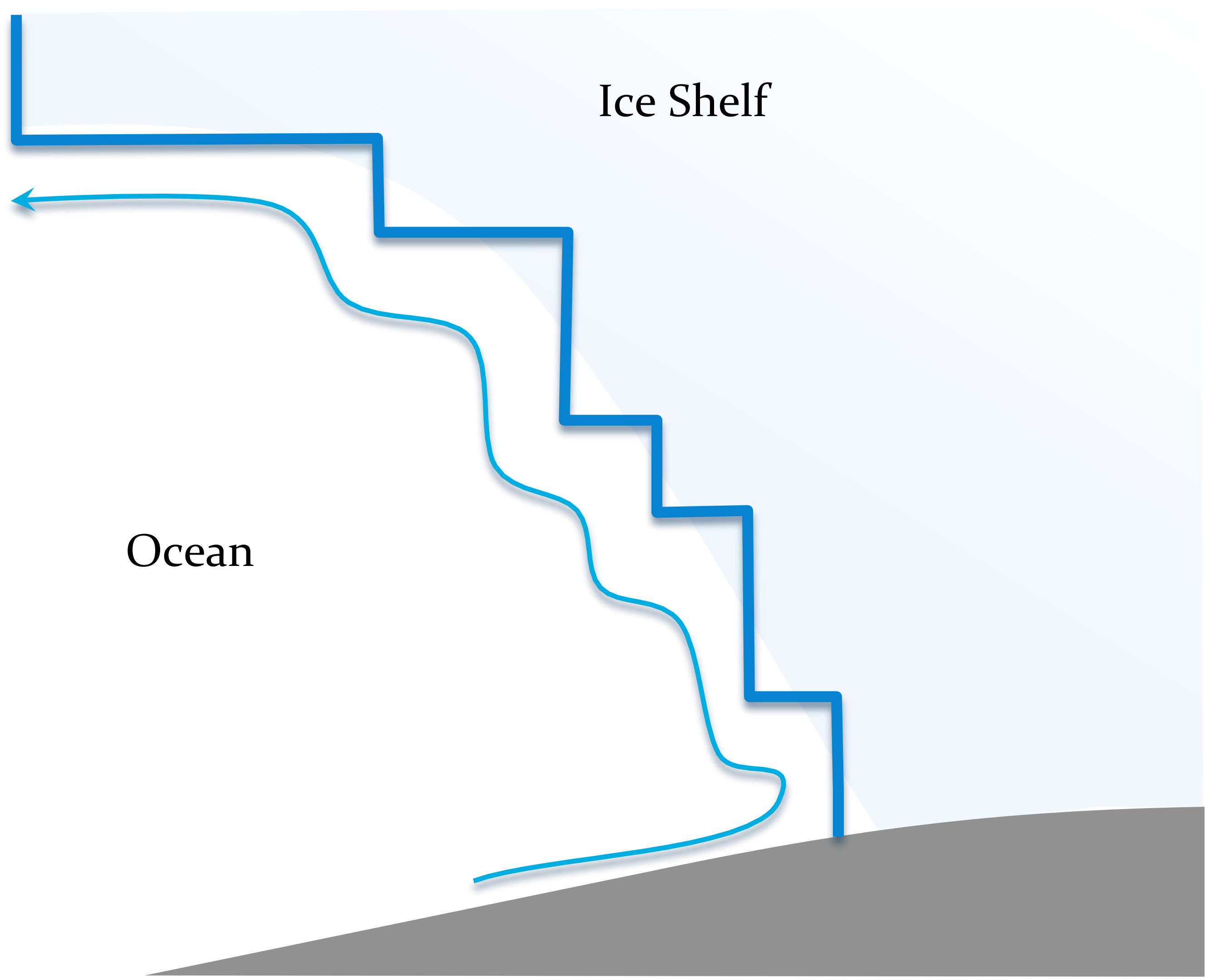
Boundary *not* at grid cell faces



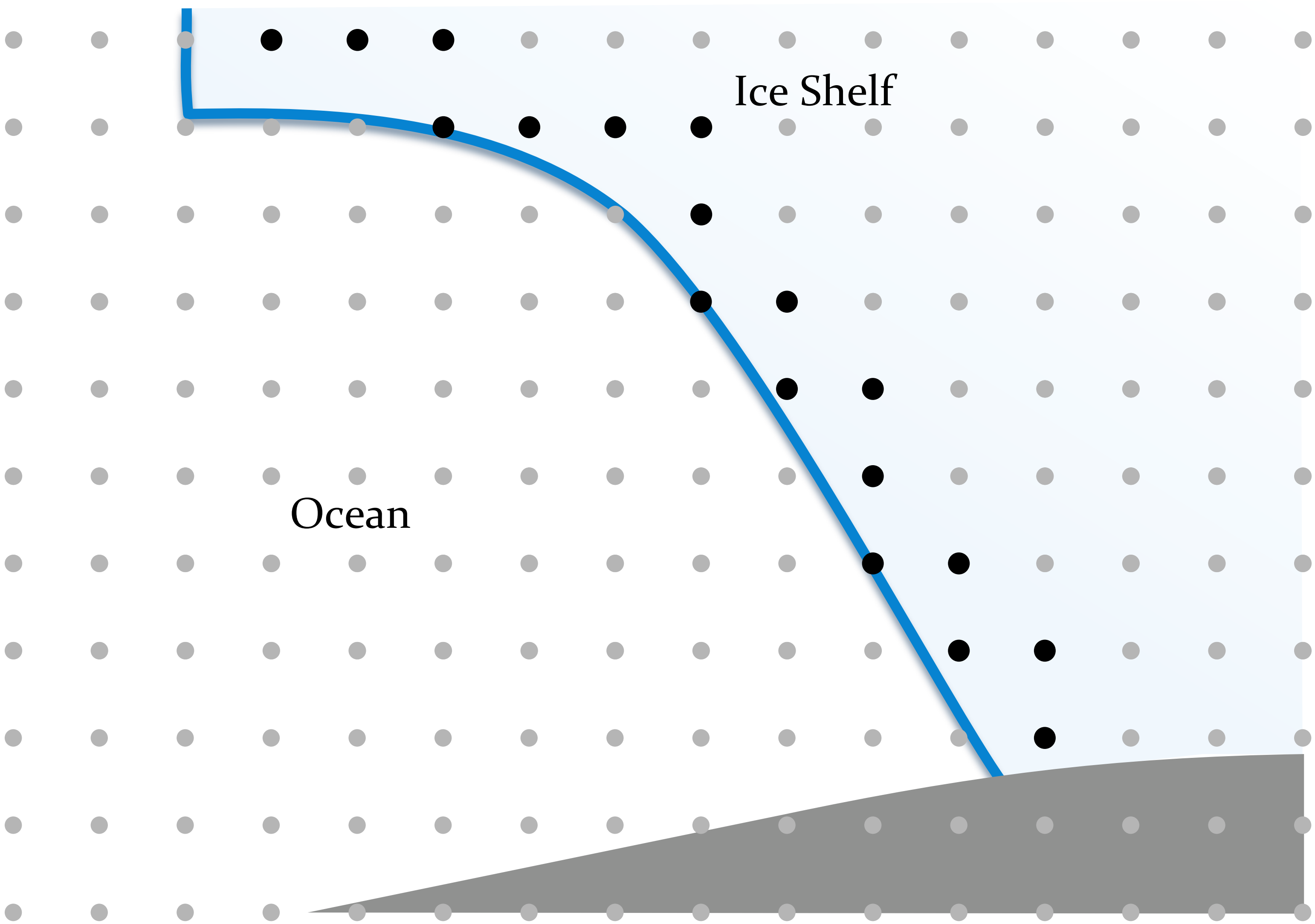
Non-IB: boundary on cell faces



Stair-step flow near boundary



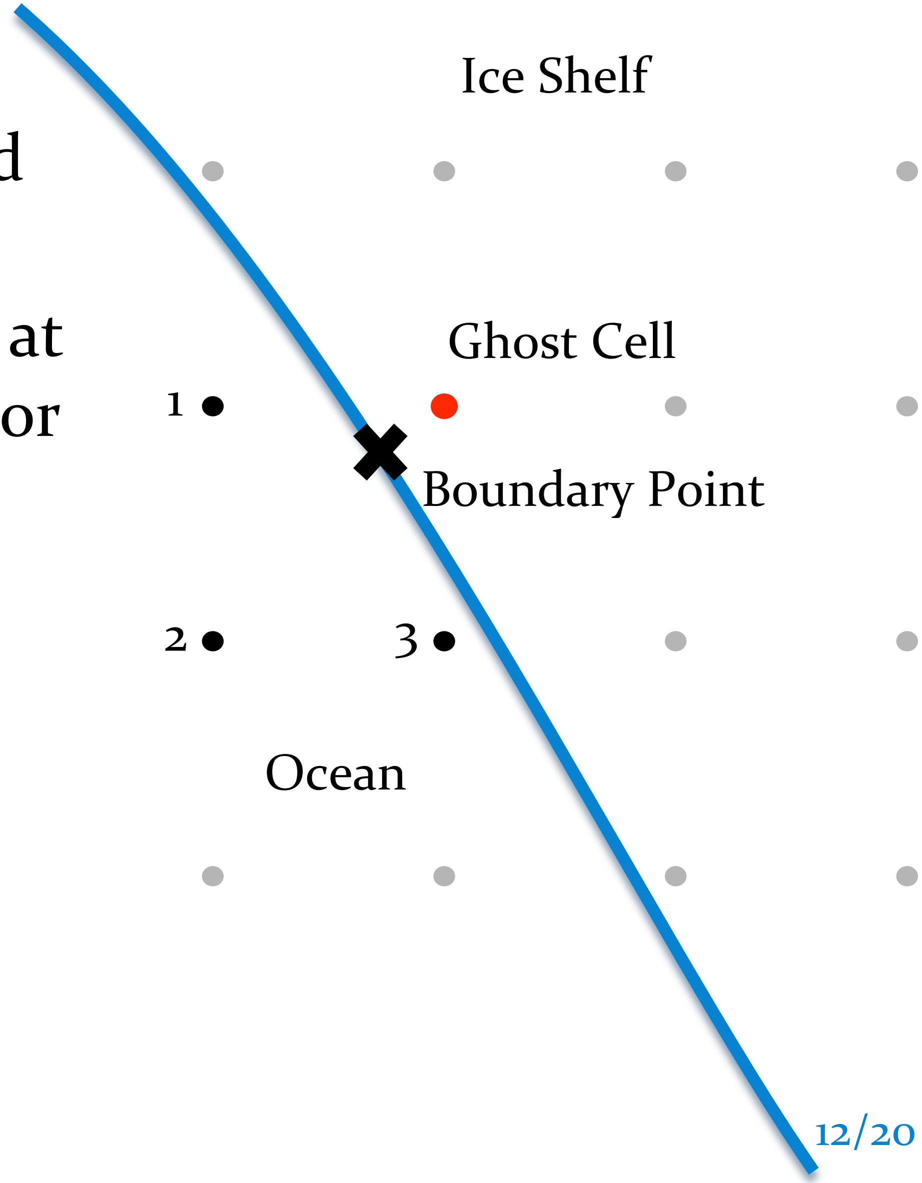
Ghost Cells neighboring interface



Finding Ghost Cell Values

- The Problem:
  - Given a function ϕ at Fluid Points 1,2 and 3
  - Given boundary condition at Boundary Point (Dirichlet or Neumann)
  - Find value at Ghost Cell

- Simple extrapolation is not always stable

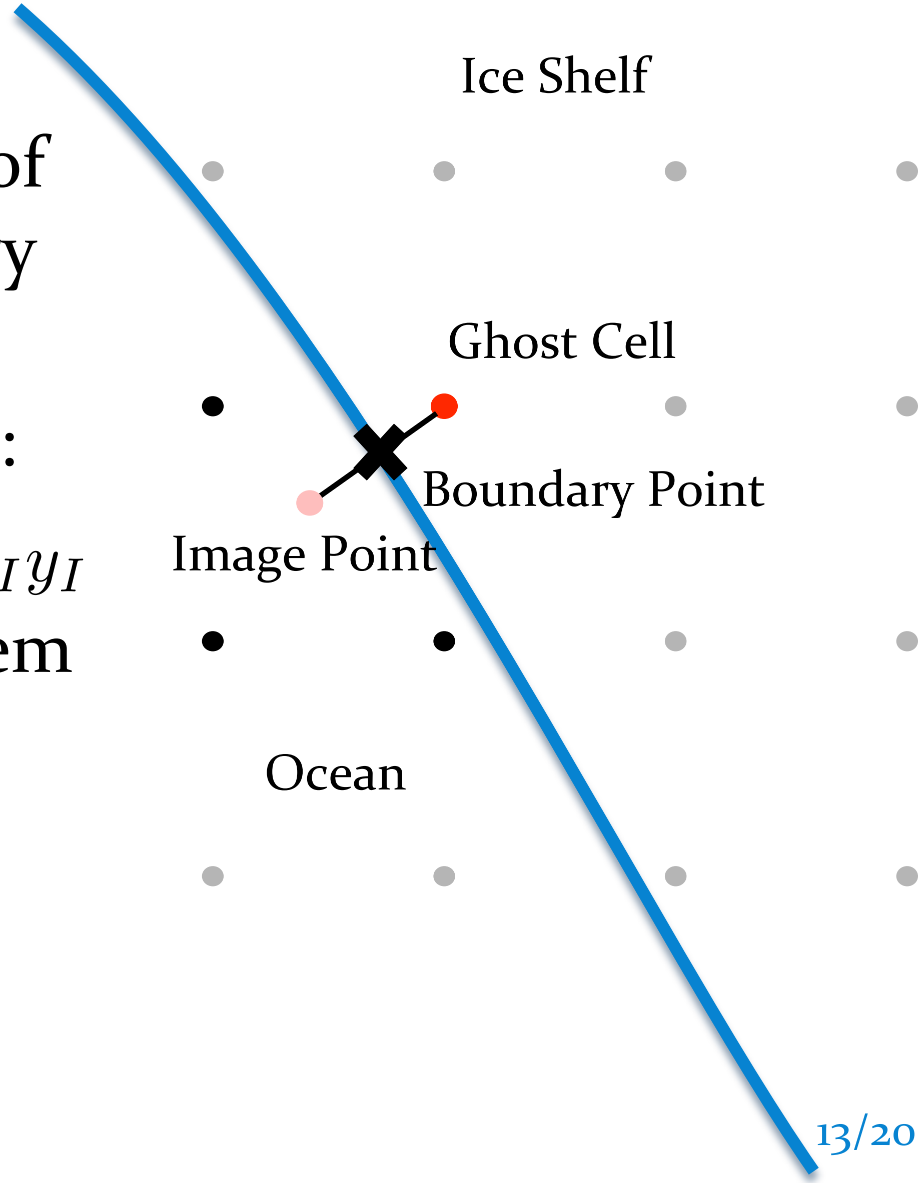


Using an Image Point

- Numerical stability
- Image point is "reflection" of ghost point across boundary
- Find image value by interpolation (e.g. bilinear):

$$\phi_I = a_0 + a_1 x_I + a_2 y_I + a_3 x_I y_I$$

- a's are found by linear system based on ϕ's, x's and y's at Fluid and Boundary Points (black)



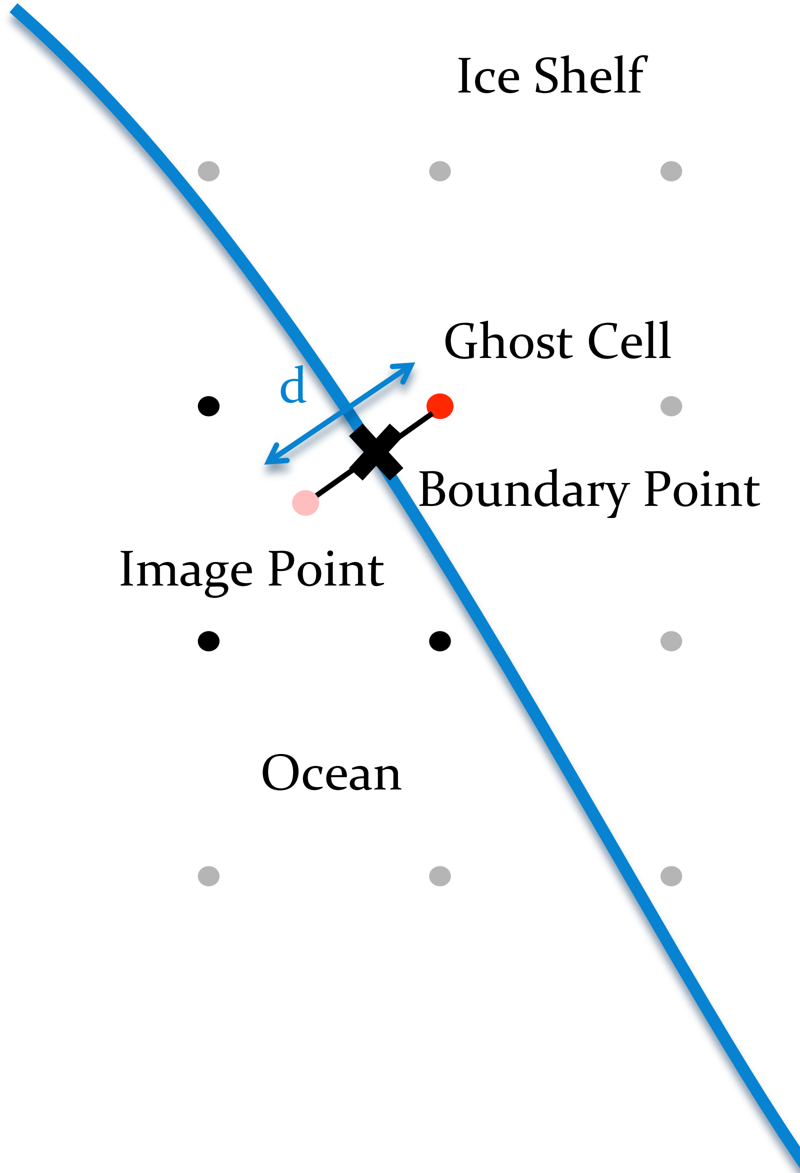
Using an Image Point

- Ghost value found by extrapolating
  - Dirichlet boundary condition:

$$\phi_G = 2\phi_B - \phi_I$$

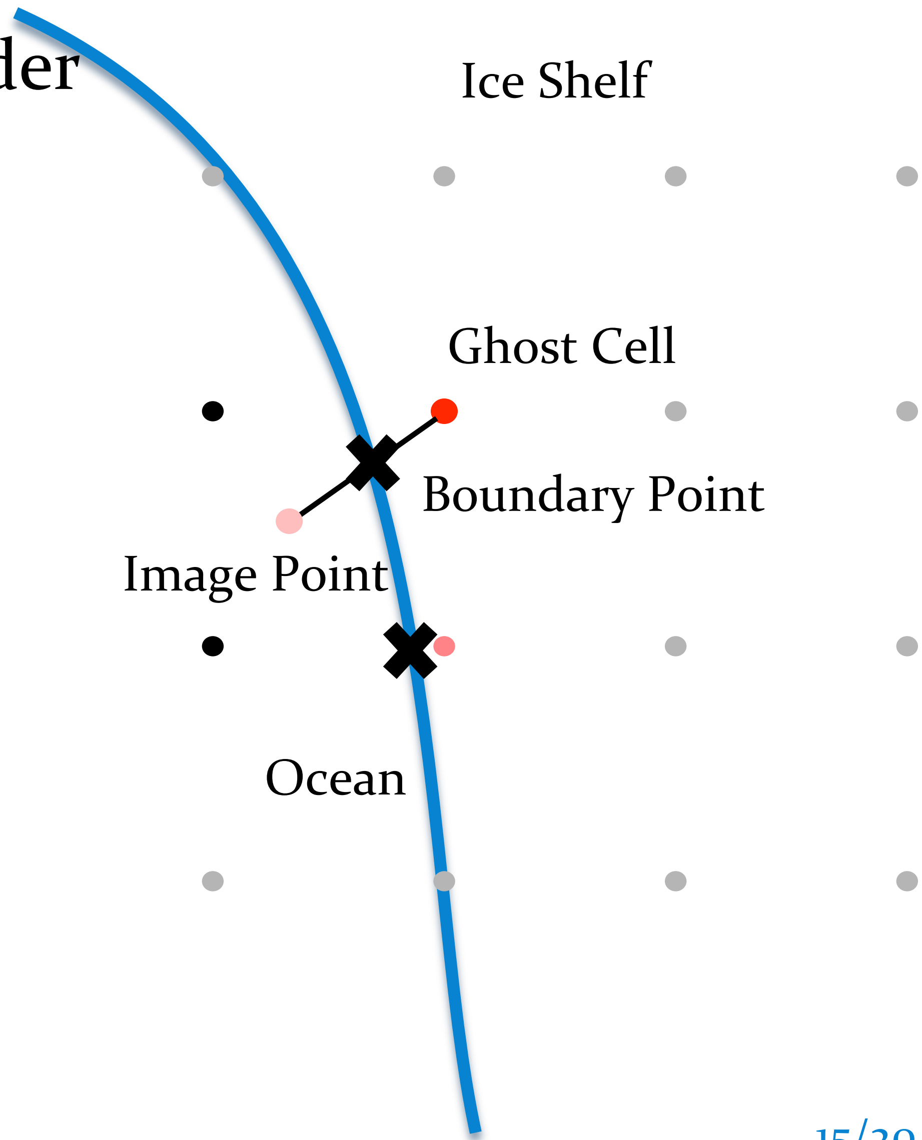
  - Neumann boundary condition:

$$\phi_G = \phi_I - d \left.\frac{\partial \phi}{\partial n}\right|_B$$



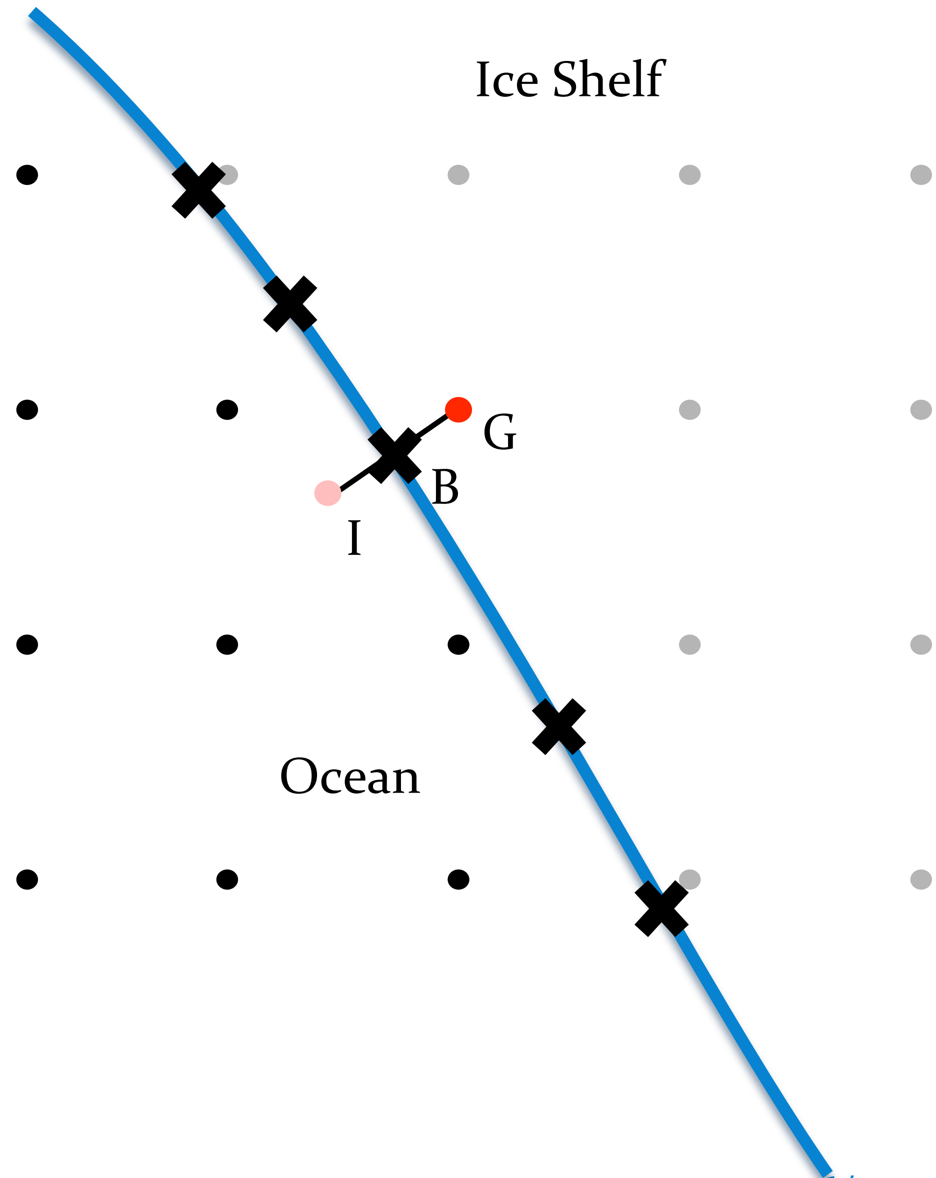
More about Image Points

- If multiple Ghost Cells border the Image Point:
  - Use multiple boundary points in interpolation



Higher Order

- Higher order interpolation of Image Points
  - Use more than 4 neighbors
  - Radial Basis Functions for interpolation
- Higher order extrapolation to Ghost Points
  - Compute $\phi_I, \left.\frac{\partial \phi}{\partial n}\right|_I$



Ice Shelf/Ocean Boundary

- Three Equation Formulation (Holland and Jenkins 1999)

$$T_B = aS_B + b + cp_B \qquad (1)$$

$$Q_I^T - Q_M^T = Q_{\text{latent}}^T \qquad (2)$$

$$Q_I^S - Q_M^S = Q_{\text{brine}}^S \qquad (3)$$

Subscripts:
M = Ocean Mixed Layer
I = Ice Shelf
B = Boundary

- Unknowns in 3 equations are T_B, S_B and w_B (melt rate)
- p_B known from weight of ice column

Ice Shelf/Ocean Boundary

- Temperature Fluxes

$$
\begin{aligned}
Q_I^T - Q_M^T =& Q_{\text{latent}}^T \qquad (2) \\
Q_I^T =& -\rho_I c_{pI} \kappa_I^T \frac{T_I - \underline{T_B}}{h_I^T} \\
Q_M^T =& -\rho_M c_{pM} \kappa_M^T \frac{\underline{T_B} - T_M}{h_M^T} \\
Q_{\text{latent}}^T =& -\rho_M \underline{w_B} L_f
\end{aligned}
$$

- (2): T_B (in temperature gradients) and melt rate w_B unknown

Ice Shelf/Ocean Boundary

- Salinity Fluxes

$$
\begin{aligned}
Q_I^S - Q_M^S =& Q_{\text{brine}}^S \qquad (3)\\
Q_I^S =& 0 \text{ ?}\\
Q_M^S =& -\rho_M \gamma_M^S \left(\underline{S_B} - S_M\right)\\
Q_{\text{brine}}^S =& \rho_M \underline{w_B} \left(S_I - \underline{S_B}\right)
\end{aligned}
$$

- (3): S_B and w_B unknown
- (1), (2) and (3) are solved together for S_B, T_B and w_B
- S and T can be extrapolated to ghost cells, w_B is used to update boundary geometry

IBs and the Three Equations

- Must find ghost values of S and T based on boundary conditions solved simultaneously

- Note: gradients occur over boundary layer width h so values of $\partial T/\partial n$, etc. cannot be found by usual finite differences