Simulation of the Wake of an Accelerating Body in a Stratified Fluid

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Motivation

Effect of small momentum excess

It is sometimes stated that a small amount of injected momentum during acceleration/deceleration changes wake behavior qualitatively towards longer lifetime and large coherent structures. Is this correct?

Wake studies usually consider steady-state towed or self-propelled cases despite this being an unrealistic assumption due to unsteady upstream conditions, slight imbalances in thrust and drag, and the presence of maneuvers.

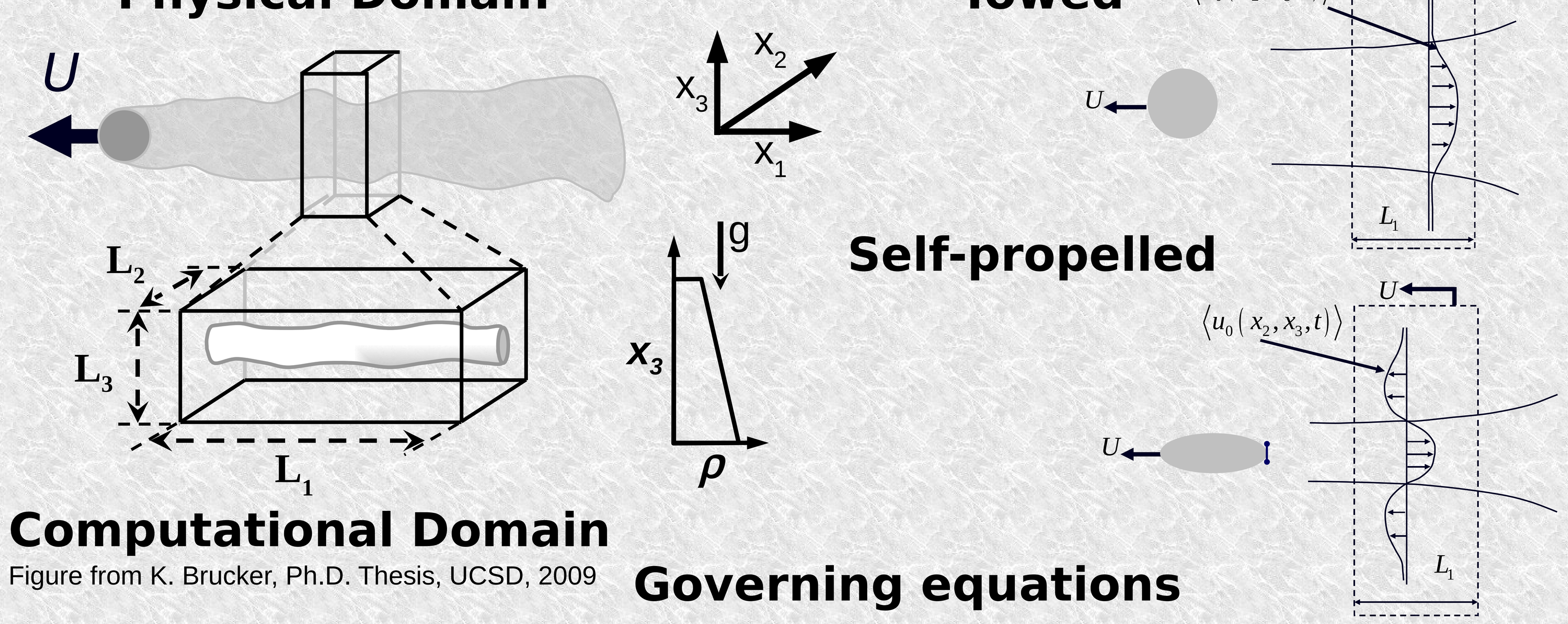
Prandtl number effect

Is the assumption of Pr=1 adequate in numerical models although Pr=7 for thermal transport in water?

Computational cost scales as Pr² using DNS $\eta_\rho = \eta/\sqrt{Pr}$

Formulation

Physical Domain **Towed** **Self-propelled**



Computational Domain

Figure from K. Brucker, Ph.D. Thesis, UCSD, 2009

Governing equations

Momentum $$\frac{\partial u_i}{\partial t} + \frac{\partial (u_k u_i)}{\partial x_k} = -\frac{\partial p}{\partial x_i} + \frac{1}{Re}\frac{\partial^2 u_i}{\partial x_k \partial x_k} - \frac{1}{Fr^2}\tilde{\rho}\delta_{i3}$$

Density $$\frac{\partial \rho}{\partial t} + \frac{\partial (u_k \rho)}{\partial x_k} = \frac{1}{RePr}\frac{\partial^2 \rho}{\partial x_k \partial x_k}$$ **Mass** $$\frac{\partial u_k}{\partial x_k} = 0$$

$$Re = \frac{UD}{\nu}, \qquad Fr = \frac{U}{ND}, \qquad Pr = \frac{\nu}{\kappa}$$

Computational domain size

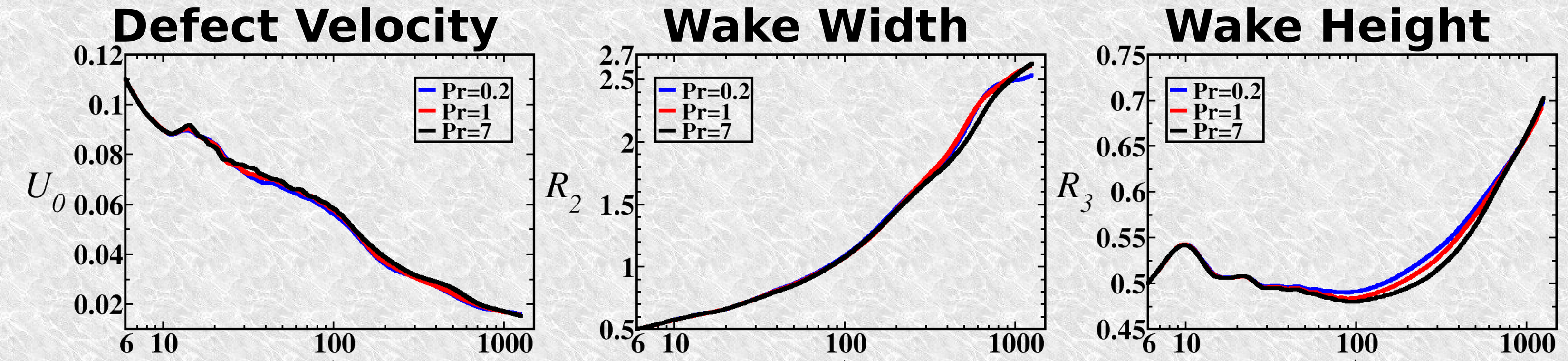
Pr=7:	3584 x 1024 x 512, 1.88	billion grid points
Pr=1,0.2:	1280 x 512 x 256, 168	million grid points
Excess momentum:	1024 x 384 x 192, 75	million grid points

Computational cost per simulation

Pr = 7:	448 processors,	14,000 computing hours
Pr = 1, 0.2:	40 processors,	800 computing hours
Excess momentum:	24 processors,	200 computing hours

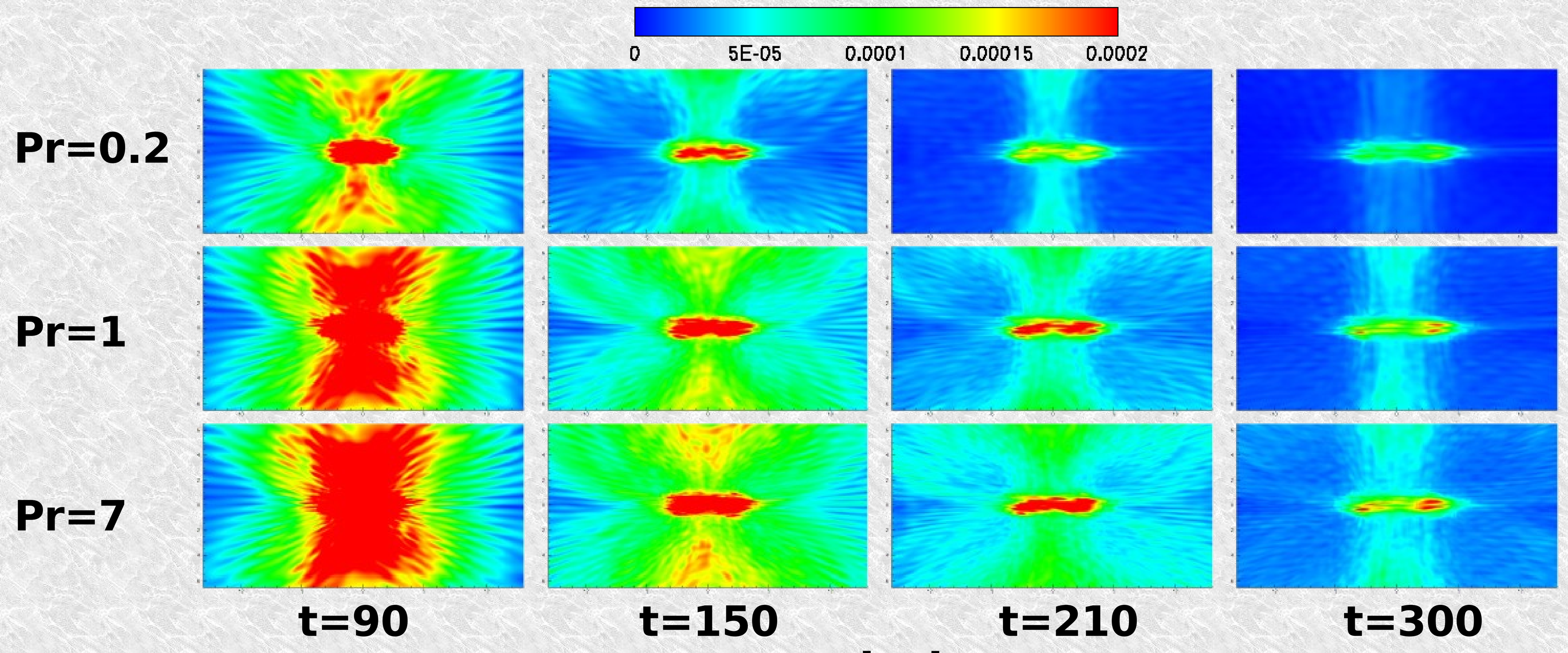
Prandtl number effect

Towed wake with Re=10,000, Fr=2, and Pr = 0.2, 1, 7,



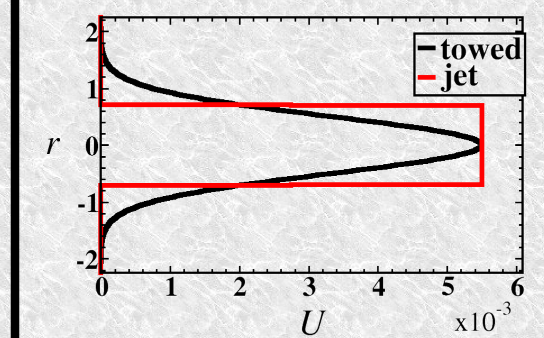
Despite slight differences, qualitative behavior is the same among the 3 cases.

Pr strongly affects the density field



ρ_{rms} evolution

Adding excess momentum



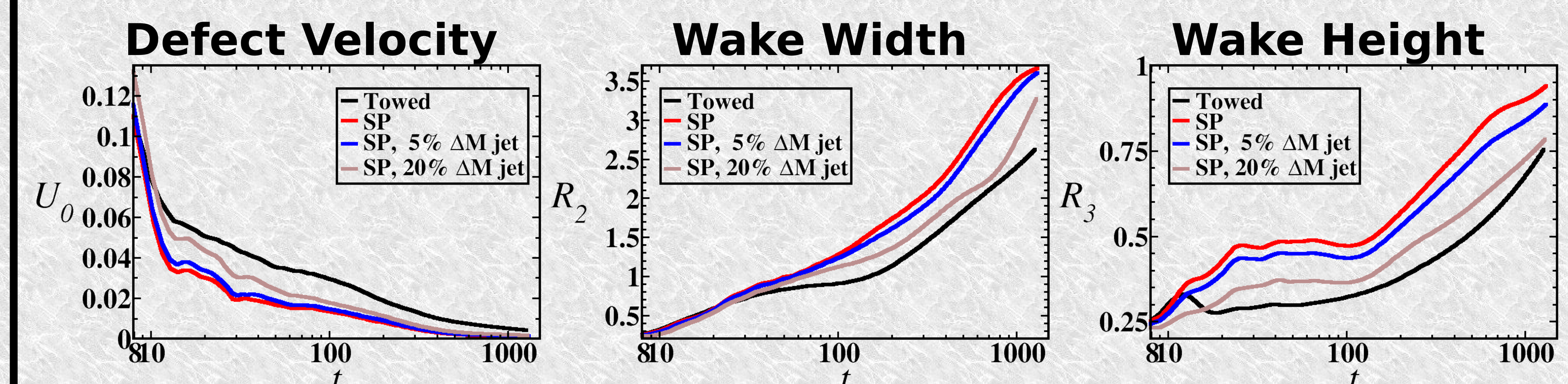
Model maneuvers as an impulsive movement

Add a percentage of the momentum in the thrust lobe to the self-propelled profile

Two cases were considered for excess momentum
Towed profile
Jet profile

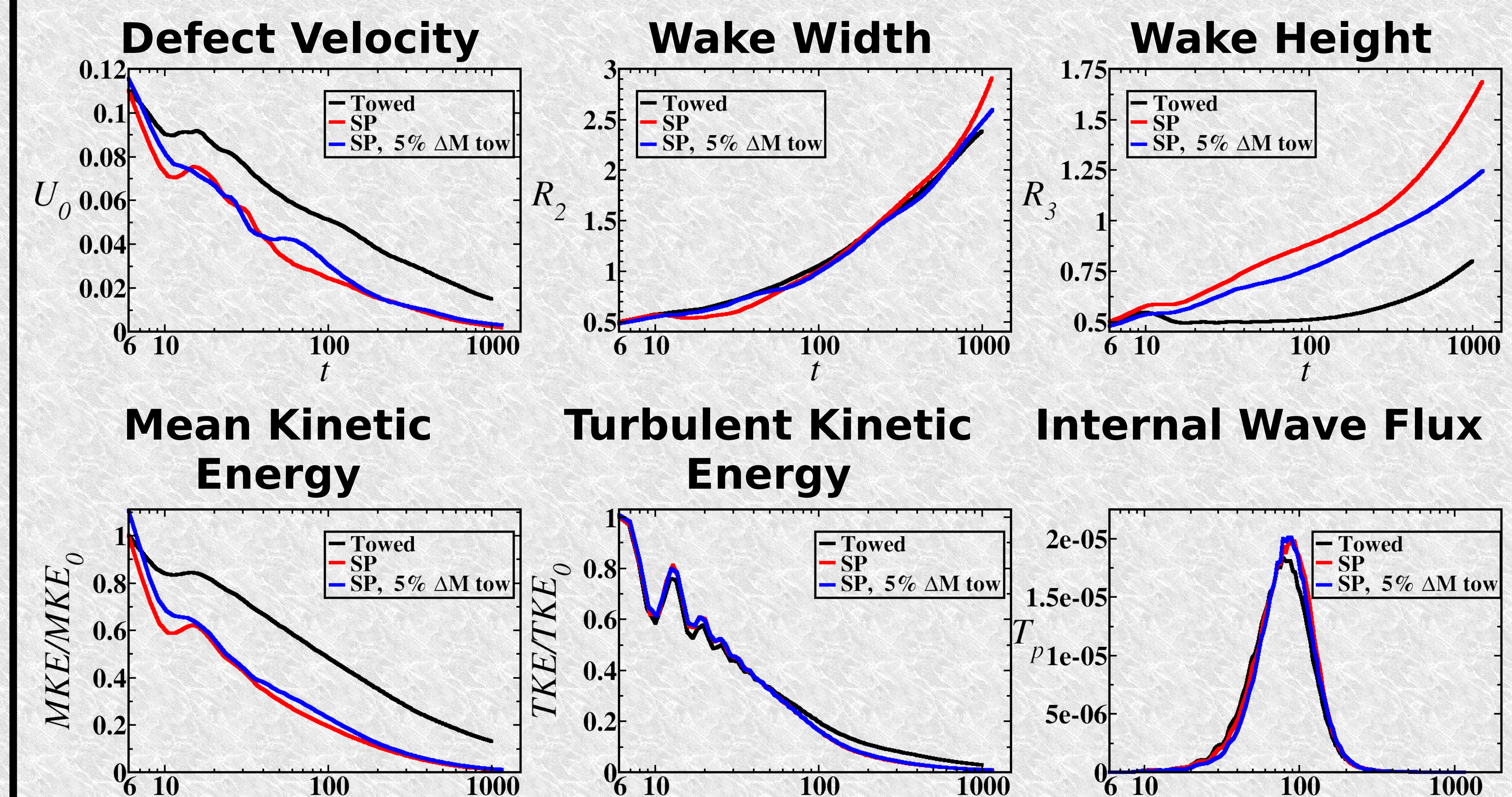
All excess momentum simulations were conducted with Re=5,000, Pr=1, and Fr=2

Excess momentum: jet



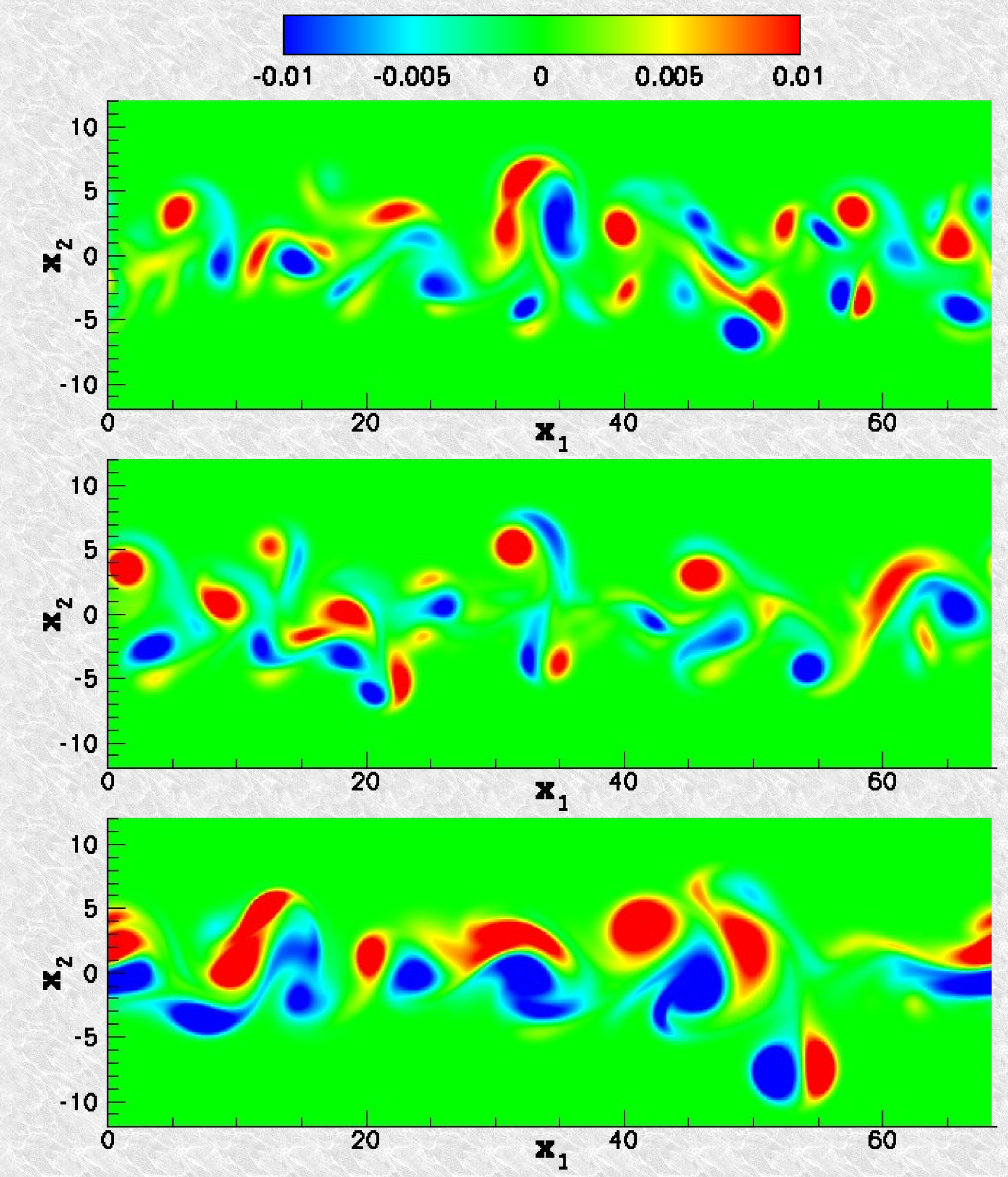
5% ΔM jet similar to SP case, 20% ΔM jet behaves qualitatively like SP but with smaller wake dimensions

Excess momentum: towed wake



5% ΔM tow similar to SP case
Turbulence quantities unaffected by excess momentum

Do large eddies form in the late wake?



Late wake vorticity: ω_3 (x_3=0) at t=800

Large scale eddies are not observed in the late wake with a small amount of excess momentum

Conclusions

Effect of small momentum excess

Principal conclusion: Neither large coherent structures nor a longer lifetime were observed

- **A small amount of excess momentum added to a self-propelled profile does not dominate wake evolution**
- **Turbulent quantities unaffected by small excess momentum**
- **Wake dimensions and defect velocity weakly affected by small excess momentum**

Prandtl number effect

Principal conclusion: For Pr < 1 or Pr > 1, the wake behaves qualitatively the same as Pr=1

Larger Pr gives (see [1] for figures and details)
Higher internal wave flux
Higher turbulent dissipation
Higher turbulent energy
Lower mixing efficiency
Positive buoyancy flux bias
Kolmogorov scaling for longer in E(k) and $E_\rho(k)$

[1] M.B. de Stadler, S. Sarkar and K.A. Brucker, Effect of the Prandtl number on a turbulent stratified wake. *Physics of Fluids,* 2010 (under review).

Future work

- **Determine parameters governing transition between momentum dominated and self-propelled wake**
- **Perform spatially evolving simulations with a constant forcing**
- **Higher Reynolds number simulations**

Acknowledgments

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