A) Modeling: existing approaches, confidence in these approaches, validation of these models, and future prospects for improving existing models.

Two-fluid or Eulerian-Eulerian approach: There is considerable need for improvement in the basic formulation of this approach. One of the fundamental problems in this approach is that the expectation, measure and ensemble are not precisely defined. A rigorous measure-theoretic re-formulation of the EE multifluid approach is essential. The expectation means surface statistics for some terms, and phase-volume average for others. For second-moment equations, this is particularly problematic.

The lack of satisfactory resolution of the so-called ill-posedness of the EE equations (as evidenced in the canonical 1D two-phase flow) needs to be addressed. This ill-posedness has implications for the fact that steady solutions are not obtained in EE two-phase flow simulations: the solutions have to be time-averaged even for a statistically stationary flow. The existence of a stationary solution is confirmed by experimental results. This situation not encountered in RANS calculations of single-phase turbulent flow, and is indicative of the need for fundamental theoretical work in multiphase flows.

Lagrangian-Eulerian approach: Many problems arise from the point-particle approximation that is often invoked in this approach. There is a lot of confusion arising from lack of established consistency relations between Eulerian and Lagrangian approaches. This is especially evident in the case of fluid-particle correlations in turbulent two-phase flow. These correlations are invoked in single-point Eulerian closures, where they have no place since they are exactly zero. The consistency conditions arising from Lagrangian to Eulerian correspondence need to be implemented in models.

The point-particle model has been used extensively in simulations, even in so-called “DNS” of particle-laden flow (DNS of fluid with point particles). The point-particle drag model is a reasonable approximation for the drag, but in DNS its impact on the dissipation and pressure fields has not been quantified. This assumption is being called into question by both true DNS, where the exact boundary condition is imposed on each particle surface. Highly resolved PIV (by Eaton’s group, APS 2005) indicate that initial estimates of the dissipation rate from low-resolution PIV were significantly off from the dissipation obtained from high-resolution PIV, which resolves the flow around particles. These results indicate that true DNS could lead to significant correction of the dissipation rates obtained from point-particle DNS.

Coupling between Lagrangian and Eulerian equations is performed in a rather ad-hoc manner, and has not been investigated thoroughly from the viewpoint of numerical error incurred from various sources: statistical, bias and spatial/temporal discretization. Resolution requirements need to be established for accurate calculations.

The future prospects are bright, provided the multiphase community is willing to question long-held beliefs, and if the community can keep an open mind to new theoretical work and simulations that are emerging to address these concerns.

B) Experiments: what well-defined experiments exist, what experiments are needed, and

Experiments that can measure planar field information in two-phase flows are needed (not just point-wise information). Simultaneous measurement in both phases is needed.

C) Design needs: what information do design engineers need, and how much of this information is currently available from models and experiments.

We also would like your input on modeling and simulation challenges, and approaches to address these challenges for:

1) Immediate (next 3 years):
   Establish accepted numerical convergence criteria for different simulation approaches (EE and LE).
   Perform comparative tests of different models on the same canonical problem; perform experiments on the same problem but do not divulge results to modelers beforehand. Thus perform a critical assessment of modeling approaches.

2) Medium Term (next 3-6 years)
   Improve theoretical foundations of EE approach.
   Resolve well-posedness issue in EE approach.
3) Long-term (6-9 years)
   Further develop computational techniques for true DNS
   Develop appropriate filtering techniques for turbulent multiphase flow for multiphase LES

- Modeling and Simulation challenge:

  Modeling multiscale interactions in turbulent particle-laden flow, e.g. interaction of a particle with turbulent eddies of different length and time scales

  Short-term approach: develop improved closure laws for particle-eddy interaction (see for example an improved multiscale model for dilute turbulent particle-laden flows, Xu and Subramaniam, Phys. Fluids, **18**, 033301, 2006)

  Medium term approach: develop filtered equations for LES of particle-laden turbulent flows, with appropriate sub-grid scale closure models

  Long-term approach: develop automatic adaptive solvers that will appropriately select resolution and filtering for both particle and fluid phases, and automatically generate and solve appropriate equation sets with coupling and computational “closure” models.

Fluid-particle interaction: Quantify effect of neighboring particles; how do clusters form?

Need a predictive model for preferential concentration of particles in turbulence.

Need to establish what level of mathematical representation is “adequate” in both EE and LE approaches.

Then focus on the physics that is needed to “close” the models.

Particle-particle interactions:

Investigate particle-particle momentum and heat transfer using true DNS. Incorporate these results into EE and LE models.

Extending single-phase LES or DNS to include particles:
Compare true DNS to point-particle DNS and establish limits of applicability.

Fundamental re-formulation of filtering procedures in multiphase flow to extend LES to multiphase flows.

Turbulence and transition to turbulence modified by particles
Turbulent dispersion and its effects on chemical reaction rate
Chemical reactions
Radiation
Interphase momentum, heat and mass transfer
Transition to dense flow