UPGRADES FOR PARALLEL PERFORMANCE AND LOW SPEED FLOWS WITH HEAT TRANSFER

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CR/RTC5.2-NA

2nd Annual SU2 Developers Meeting

December 18, 2017

BOSCH

Agenda

1. Introduction to Bosch, CR, and RTC5.2

2. SU2 Upgrades: I/O for Parallel Performance

3. SU2 Upgrades: Low Speed Flows with Heat Transfer

4. Future Outlook

INTRODUCTION TO BOSCH, CR, AND RTC5.2

Bosch – technology to enhance quality of life

- Some 59,000[1] researchers and developers work at Bosch: at 120[2] locations worldwide, in a single network.
- Bosch is one of the world's leading international providers of technology and services.
- Over the past six years, Bosch has invested more than 27 billion euros in research and development.
- Our objective: to develop innovative, useful, and exciting products and solutions to enhance quality of life – technology that is "Invented for life."

[1] As of 12.16 [2] R&D locations with >50 associates, as of 12.16

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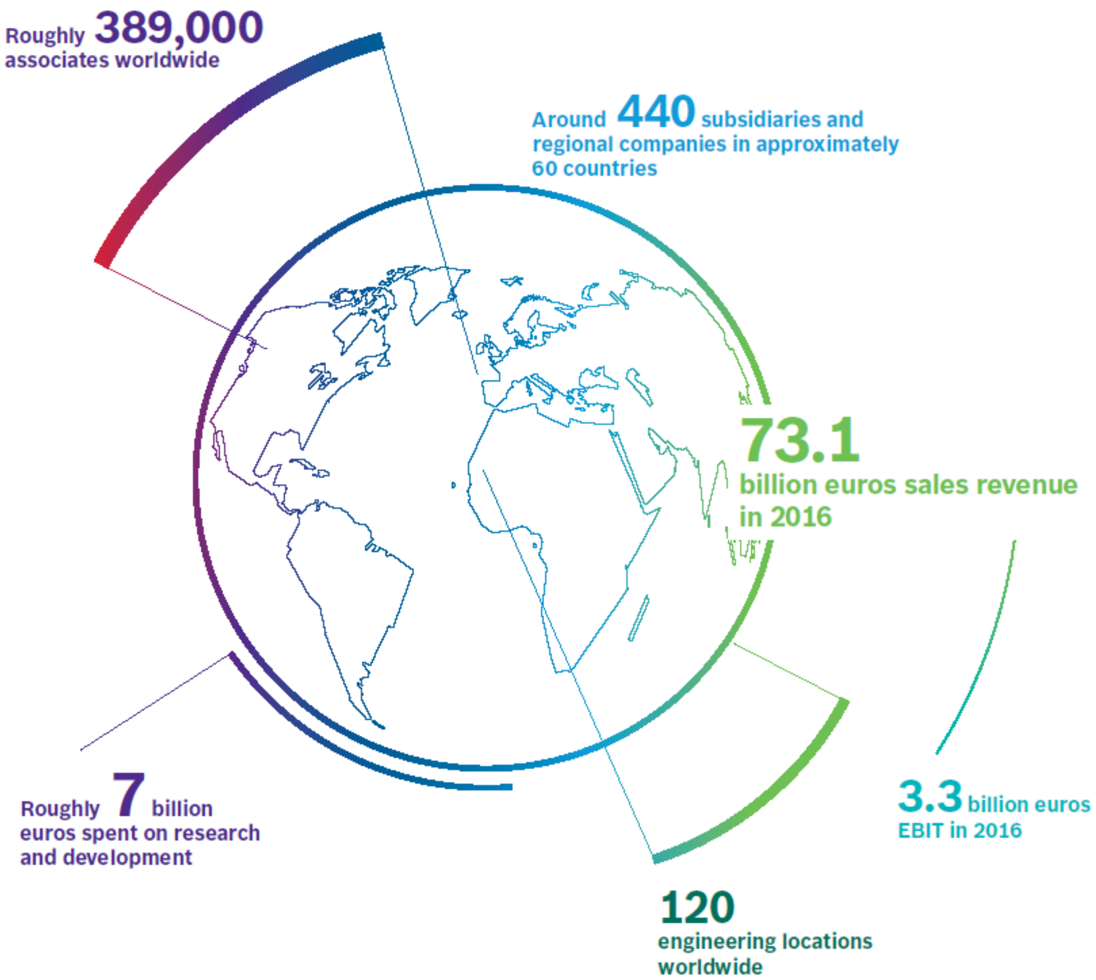
Bosch – a global network



- The 390,000[1] Bosch associates make these solutions possible.
- Bosch has four business sectors, with more than 440[1] subsidiary companies and regional subsidiaries in some 60[1] countries.

[1] As of 12.16

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Bosch – Four business sectors
Key figures 2016*

Bosch Group

- 73.1 billion euros in sales
- 389,281 associates

Mobility Solutions
- One of the world's largest suppliers of mobility solutions

60% share of sales

Industrial Technology
- Leading in drive and control technology, packaging, and process technology

Energy and Building Technology
- One of the leading manufacturers of security and communication technology
- Leading manufacturer of energy-efficent heating products and hot-water solutions

40% share of sales

Consumer Goods
- Leading supplier of power tools and accessories
- Leading supplier of household appliances

* As of 12.16

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Figures, Facts and Locations

59,000
Bosch researchers and developers worldwide

In 2016, Bosch invested
7 billion €
research and development

120
Bosch research and development locations worldwide[1]

3%
of them work in Corporate Research

In 2016,
345 million €
were invested in Corporate Research

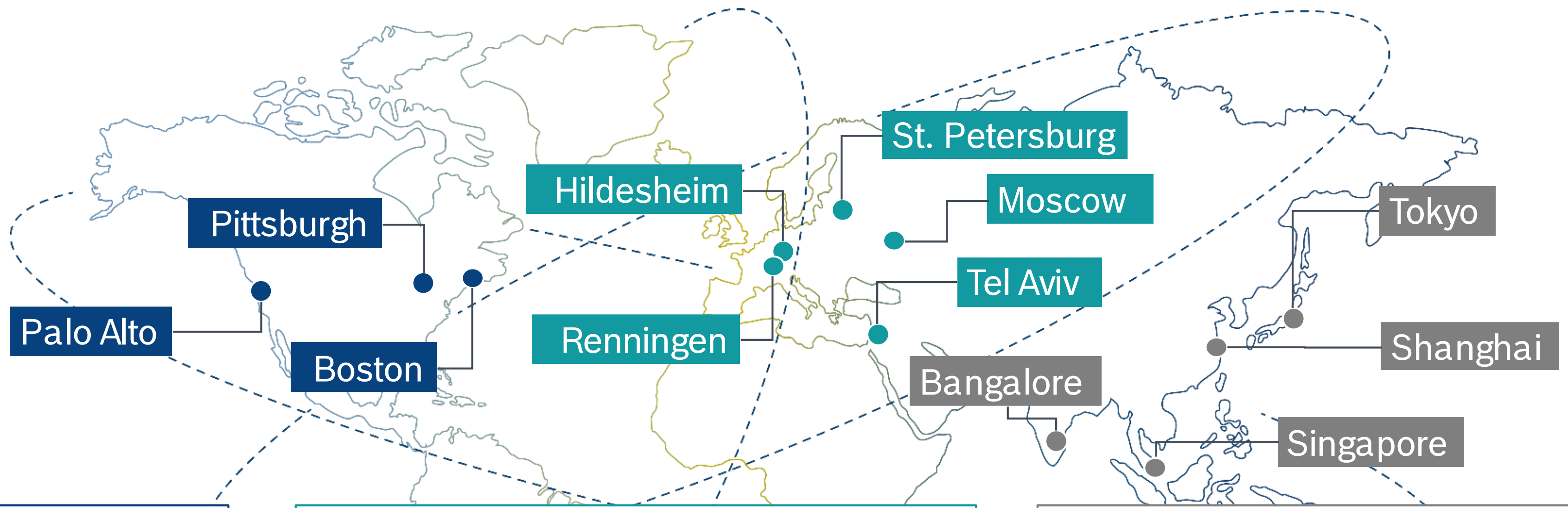
1,600
associates in Corporate Research at 12 locations in North America, Europe, Russia, Asia-Pacific and India

Of this,
5% came from public funding

Bosch creates a new invention
every 22 minutes

[1] Includes all locations with at least 50 associates (as of December 2016)

Figures, Facts and Locations



America

Research and Technology Center North America

110 associates

Europe

- Corporate research
- Research and Technology Office Russia
- Research and Technology Office Tel Aviv

1,360 associates

Asia-Pacific

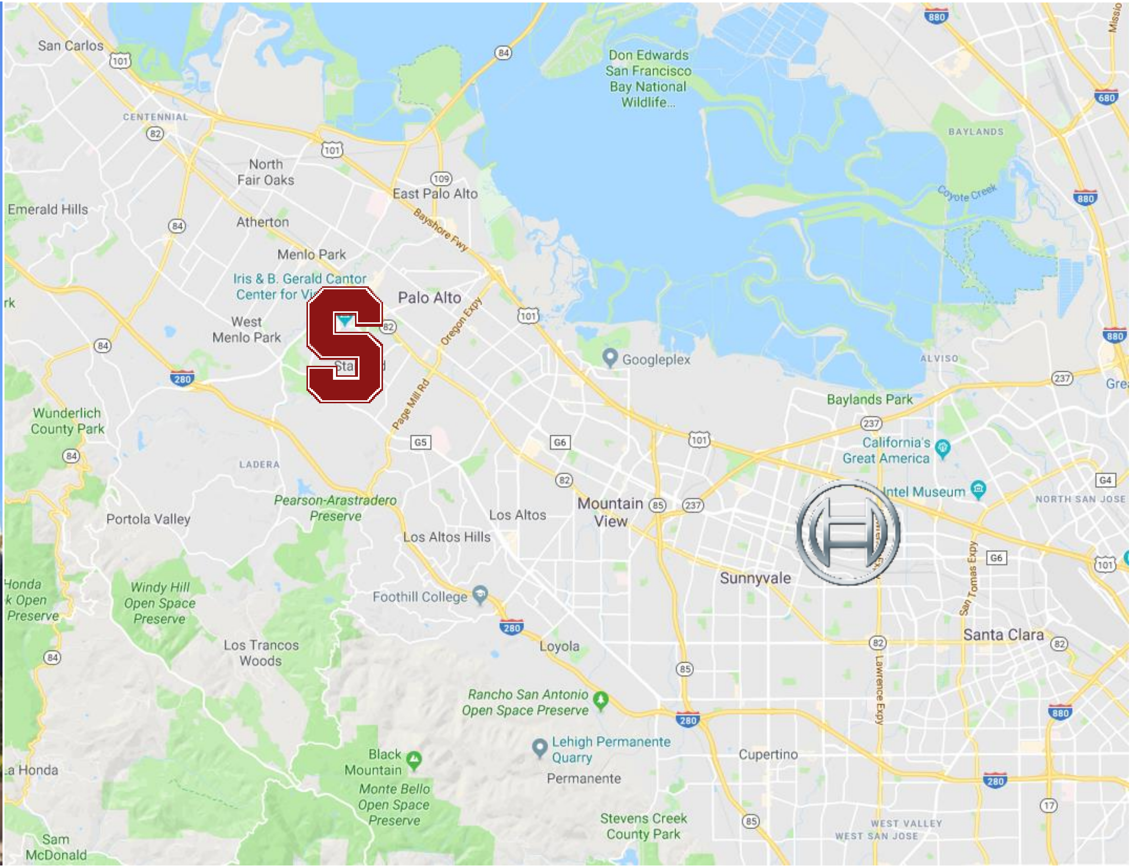
- Research and Technology Center India
- Research and Technology Center Asia-Pacific

90 associates

as of December 2016

CR/RTC-NA | Palo Alto

New location in Sunnyvale, CA



CR/RTC5.2 Group Overview
Multiphysics Modeling and Simulation

- **Associates**

Xiaobai Li

Lead Engineer

PhD: Caltech

Bosch RTC: 2010

Sergei Chumakov

Research Engineer II

PhD: U of Wisconsin

Bosch RTC: 2010

Achim Briese

Senior Engineer

MS: Georgia Tech.

Bosch RTC: 2015

Daniel Mayer

Post-doc

PhD: RWTH Aachen

Bosch RTC: 2016

Jomela Meng

Research Engineer

PhD: Caltech

Bosch RTC: 2016

Thomas Economon

Senior Research Scientist

PhD: Stanford

Bosch RTC: 2017

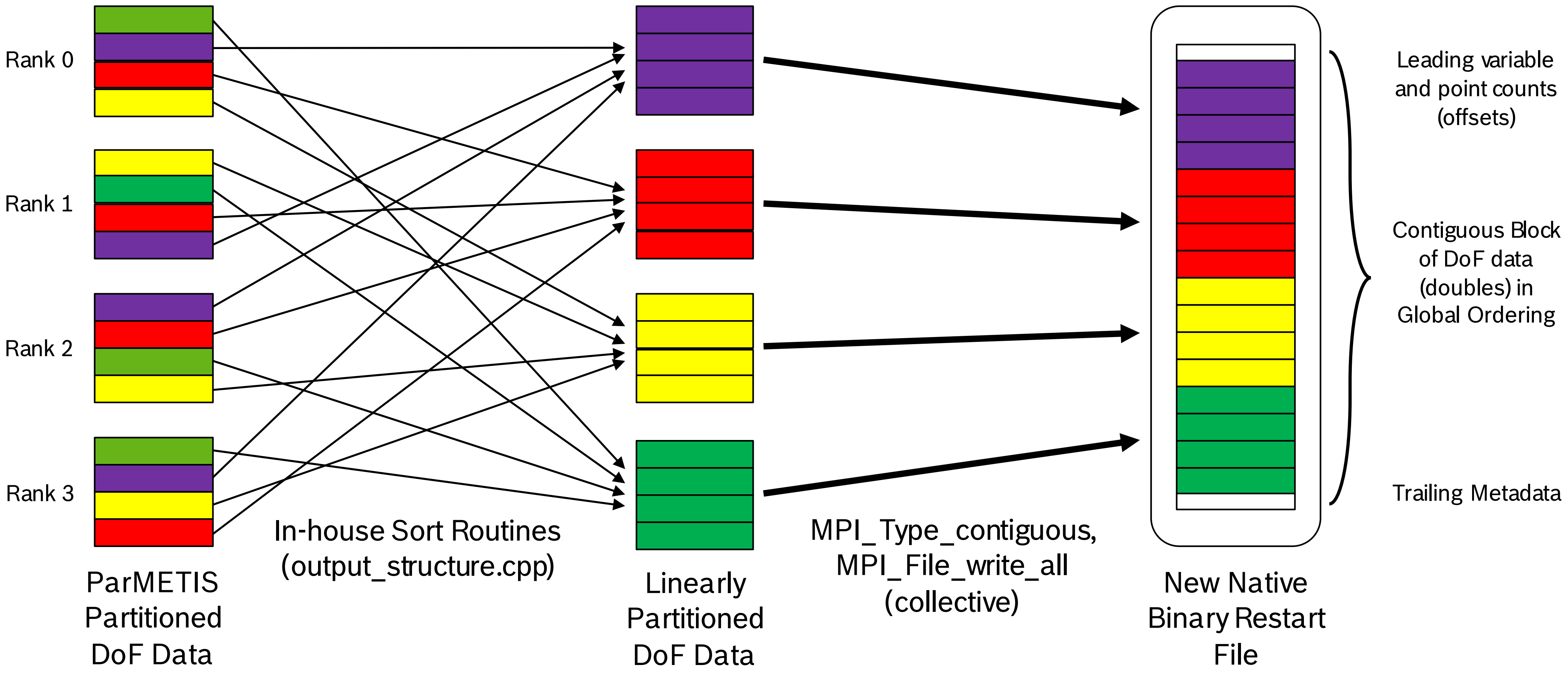
SU2 UPGRADES: I/O FOR PARALLEL PERFORMANCE

I/O for Parallel Performance
Some History

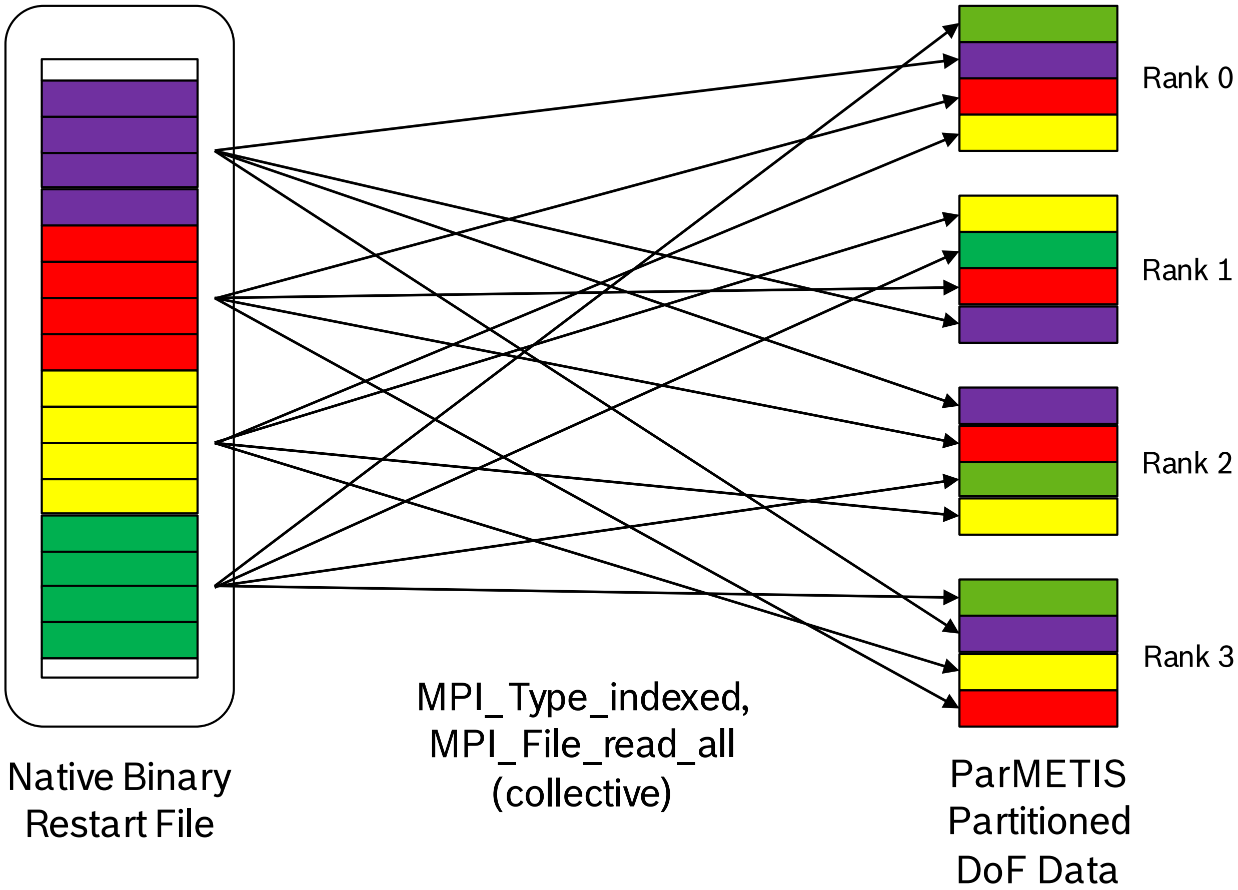
- The early days…
  - Early versions of the code had a standalone partitioning module, SU2_DDC, later renamed SU2_PRT.
  - SU2_PRT would partition in serial with METIS and write mesh files for each rank.
  - Independent parallel I/O: each rank of SU2_CFD reads/writes individual files during execution.
  - Output files merged into a single file for visualization packages (Tecplot / ParaView).

- Now (Dec 2017)…
  - SU2_CFD handles all grid input and solution data output in a fully parallel manner.
    - ASCII or binary mesh files are read in parallel, partitioned with ParMETIS, and redistributed in memory.
    - Binary restart / checkpoint files are written and read in parallel with MPI I/O.
  - SU2_SOL module can generate new visualization files at any time, in any format, from a restart.

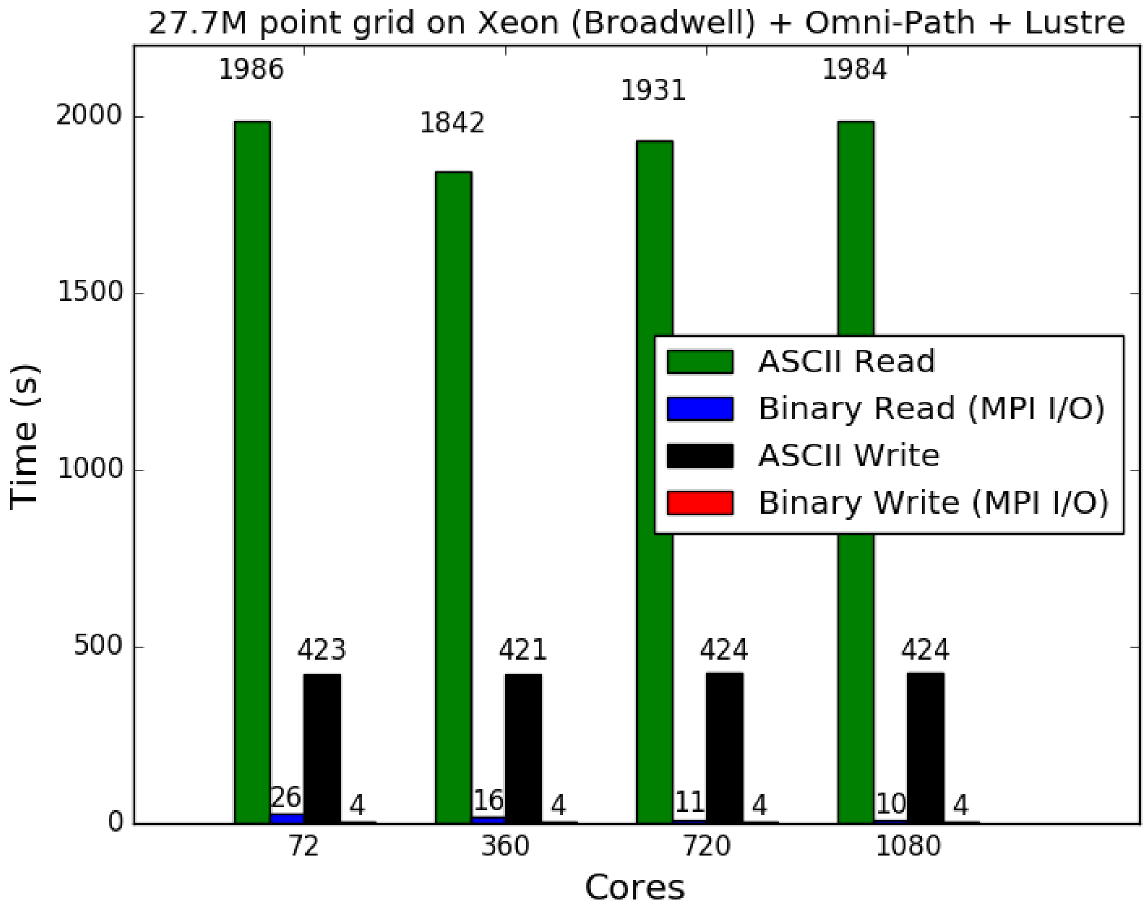
I/O for Parallel Performance
Restart / Checkpoint File Output with MPI I/O



I/O for Parallel Performance
Restart / Checkpoint File Input with MPI I/O



I/O for Parallel Performance
Parallel I/O Performance Example



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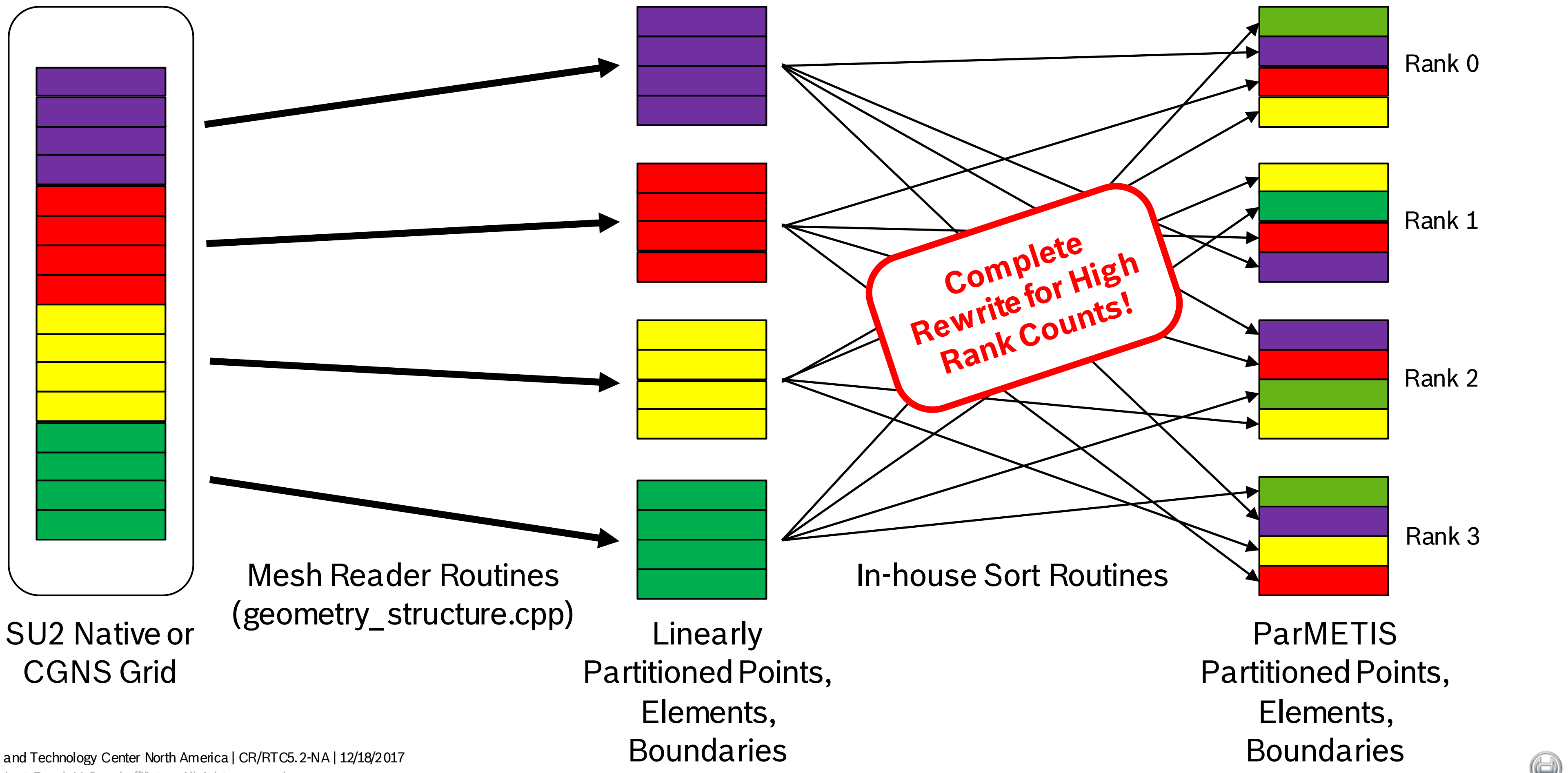
I/O for Parallel Performance

Streamlining Grid Partitioning (Just Flip It!)



SU2 UPGRADES: LOW SPEED FLOWS WITH HEAT TRANSFER

Low Speed Flows with Heat Transfer
More History

- SU2 was born out of the transonic, external CFD world in 2012:
  - Density-based flow solver that integrates continuity, momentum, and energy equations in a coupled fashion with each time step (5 coupled equations in 3D).
  - Proven algorithms and the obvious choice for compressible, high speed problems.
  - Typical 2nd-order convective schemes implemented, e.g., JST, Roe, HLLC, etc.

- After a couple of years, our interest in low Mach / incompressible problems grew.
  - But, applying a compressible code to incompressible flows does not work well!
    - Poor convergence behavior
    - Accuracy problems due to poor scaling of dissipation terms

- So, given that we already had a density-based solver, we looked into the many available techniques for modifying a compressible code to compute incompressible or mixed low/high speed flows.

Low Speed Flows with Heat Transfer
Available Techniques

- Several approaches implemented into SU2:
  - Artificial Compressibility (AC).
  - Low Mach preconditioning.
  - Other low Mach corrections, such as for upwind reconstructions.
  - Low Mach Roe scheme.

- Where do we go from here?
  - AC promising but missing features.
  - Other current treatments seem best for mixed low/high-speed flows.
  - Pressure-based incompressible solver being worked on in the open-source, but will take time.


(Reprint of 1967 paper)

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A low-Mach number fix for Roe's approximate Riemann solver

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ABSTRACT

We present a low-Mach number fix for Roe's approximate Riemann solver (LMRoe). As the Mach number Ma tends to zero, solutions to the Euler equations converge to solutions of the incompressible equations. Yet, standard upwind schemes do not reproduce this convergence: the artificial viscosity grows like 1/Ma, leading to a loss of accuracy as Ma → 0. With a discrete asymptotic analysis of the Roe scheme we identify the responsible term: the jump in the normal velocity component ΔU of the Riemann problem. The remedy consists of reducing this term by one order of magnitude in terms of the Mach number. This is achieved by simply multiplying ΔU with the local Mach number. With an asymptotic analysis it is shown that all discrepancies between continuous and discrete asymptotics disappear, while, at the same time, checkerboard modes are suppressed. Low Mach number test cases show, first, that the accuracy of LMRoe is independent of the Mach number, second, that the solution converges to the incompressible limit for Ma → 0 on a fixed mesh and, finally, that the new scheme does not produce pressure checkerboard modes. High speed test cases demonstrate the fall back of the new scheme to the classical Roe scheme at moderate and high Mach numbers.

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1. Introduction

In some applications compressible and weakly compressible flow regimes exist in a single computational domain. Low Mach number regions in high speed flow are, for example, stagnation points and the wake behind bodies. In other applications the flow regime can suddenly change from quasi incompressible to compressible such as in the case of deflagration–detonation transition (DDT). This explains the need for solvers that can handle both, the capturing of shock waves in high speed flows as well as the accurate simulation of weakly compressible flow structures.

Unfortunately, schemes designed to capture shock waves face a number of problems if applied to low-Mach number flow regimes, i.e. if the Mach number tends to zero: stiffness of the equations, cancellation in the pressure variable and the loss of accuracy due to numerical diffusion of the order $\mathcal{O}(1/\mathrm{Ma})$. The research efforts to overcome these difficulties are enormous and the approaches are diverse.

The *cancellation problem* was solved by Sesterhenn et al. in [1]. They avoid it by working only with the fluctuation quantities introduced in the wave propagation approach by LeVeque [2].

To overcome the *stiffness and accuracy problem in steady flow simulations* a variety of time-derivative or flux preconditioning techniques have been developed and applied to compressible (and incompressible) solvers for the inviscid flow equations, such as Turkel's approach, [3,4], or the characteristic time stepping approach by van Leer et al. [5]. The stiffness is reduced by (almost) equalizing the propagation speeds of the different waves for Ma → 0, which accelerates the convergence to steady state. At the same time, the artificial viscosity is tuned correctly for all characteristic waves and thus the accuracy

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Low Speed Flows with Heat Transfer
Levels of Approximation for Navier-Stokes

	Incompressible Navier-Stokes	Low Mach Navier-Stokes	Compressible Navier-Stokes
Primitive Variables	V = (p, u, v, w)	V = (p, u, v, w, phi)	V = (p, u, v, w, T)
Density	density = constant	density = f(phi)	density = f(p, T)
Pressure	p completely decoupled from density and T (hydrodynamic only, no acoustics)	Hydrodynamic p in momentum, but thermodynamic p can appear in EoS (still no acoustics)	p coupled to both density and T through EoS for the fluid to close the system (e.g., perfect gas)
Energy	Not required. Decoupled energy eqn. or Boussinesq approx. possible for convection.	Simplified form for phi (phi could be T). Use phi to compute density with EoS.	Fully-coupled equation for total energy (internal + kinetic)
Available in SU2?	✓	✗	✓

Low Speed Flows with Heat Transfer
New Developments

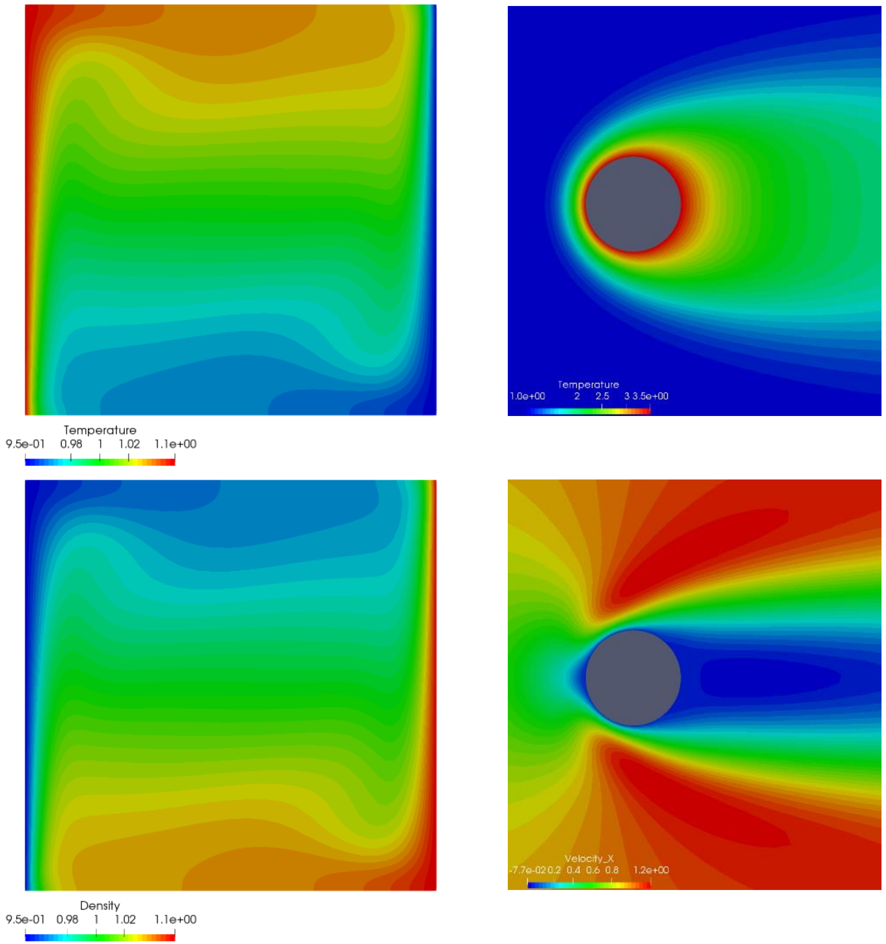
- A generalized method for low speed flows with heat transfer:
  - Simplicity: fully compressible N-S not required
  - Euler, N-S, and RANS (Low Mach)
  - Conservative formulation
  - Primitive variable-based (p, u, v, w, T)
  - Custom Flux Difference Splitting (upwind) and centered schemes
  - Implicit & explicit time integration

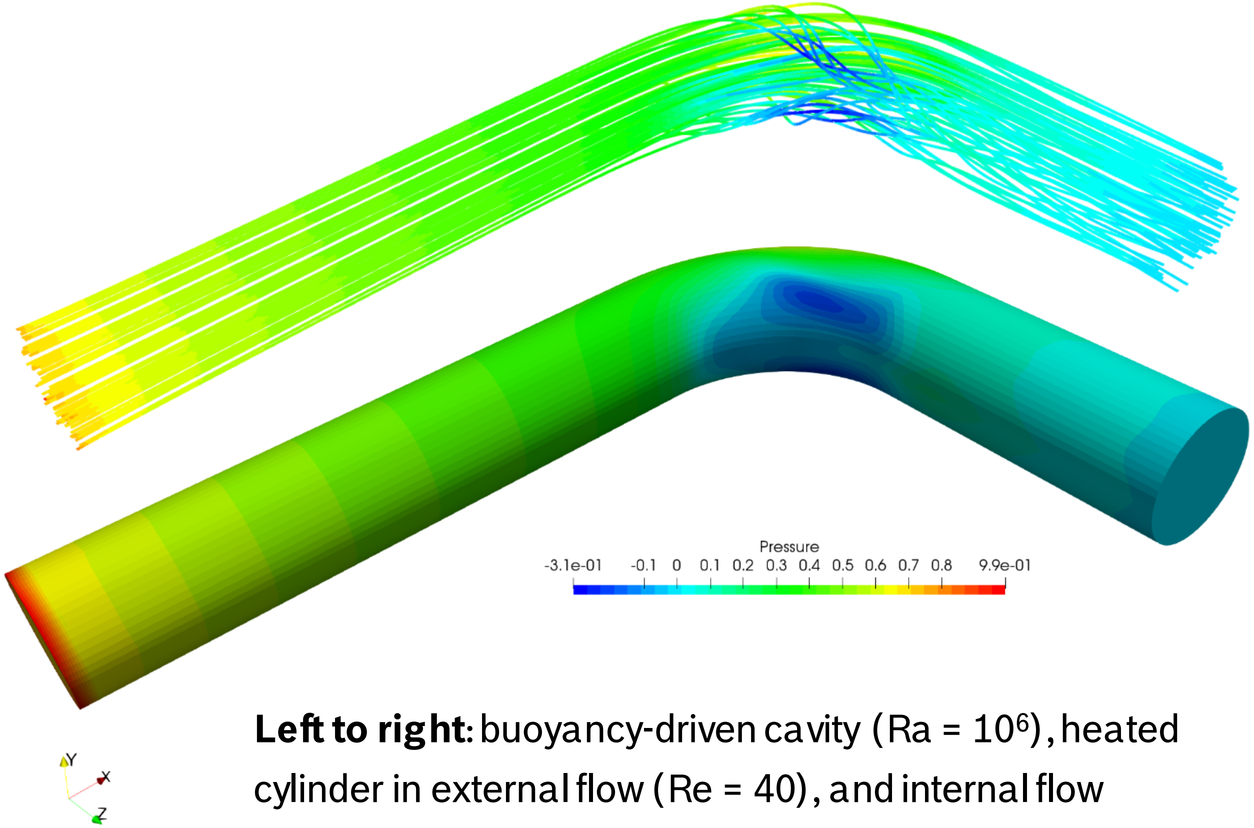
Still Under Development, But Preliminary Results Promising!

- Enables variable density incompressible flows:
  - Introduces 2 new fluid models: constant density fluid, incompressible ideal gas
  - New non-dimensionalization and initialization routines
- Includes energy equation:
  - New energy eqn. options to disable, decouple, apply Boussinesq approximation, or couple for variable density
  - Heat flux and isothermal wall BCs added

Low Speed Flows with Heat Transfer

Sample Results





Left to right: buoyancy-driven cavity (Ra = 10^6), heated cylinder in external flow (Re = 40), and internal flow through pipe bend (Re = 400).

FUTURE OUTLOOK

Future Outlook

- Some feedback and challenges to our entire development team…
  - We all enjoy coding new features, but **usability is critical**!
    - E.g., config option clarity, helpful error messages, automatic parameter tuning, ease of use of adjoint methods.
  - Sometimes compute resources are limited: focus on efficient implementations.
  - Continue improving interfaces for multi-zone / multiphysics / knowledge extraction.

- Some development topics for 2018 (collaboration welcome):
  - Continued work on low speed flows with heat transfer.
  - Partitioning rewrite was a precursor to improving periodic boundary condition in parallel.
  - Improved wall treatments, BCs, and more.

- We support the SU2 community!