APRIL
2007

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MICROSOFT

A Winning Combination

LS-DYNA® and Windows

Compute Cluster Server 2003 (CCS)

2007 ANSYS

U.S. Regional

Conference Series:

PENNSYLVANIA

Linux Networx

LS-1 Supersystems

FEA INFORMATION RESOURCE MAGAZINE

Announcements:

From FEA to MCAE Today - A 40-Year Personal Odyssey

Based on the popularity of Part 1 From FEA to MCAE Today, we have made an editorial decision to bring you the complete article.

To conserve space and pages in this issue we have opted to leave out sections. These sections will continue in the May edition.

Wecome FEA Information Participants

SUN Microsystems - HPC and Technical Computing
Complete Article will appear in May Edition

Cranes Software – INDIA – ETA Products – LS-DYNA and others

“2nd ANSA & μETA International Congress”

June 14-15, 2007, in Halkidiki, Greece.

Sincerely,

Art Shapiro
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AMD Benchmark Neon Refined

AMD LS-DYNA version 971 Benchmark

AMD Marks AMD64 Anniversary With Widespread Availability Of New Highest-Performing AMD Opteron™ Processor

Complete Press Release can be located on the AMD website:

—AMD Also Updates 'Barcelona' Native Quad-Core Performance Projections—

Sunnyvale, Calif. -- April 23, 2007 -- Marking with the fourth anniversary of the launch of the AMD Opteron™ processor and AMD64 technology, AMD (NYSE:AMD) today announced widespread availability and pricing for the performance-leading AMD Opteron Model 2222 and 8222 SE x86 dual-core server processors. The new processor, which is available in several platform configurations today from tier one OEMs, is designed to deliver performance leadership in the most critical server functions including Web serving, scalability and floating point calculations.

AMD also disclosed updated performance projections for its upcoming native Quad-Core AMD Opteron™ processors, code-named 'Barcelona.' The new Barcelona projections are based on the latest SPECcpu2006 benchmarks and show that AMD expects to have up to a 50 percent advantage in floating point performance and 20 percent in integer performance over the competition's highest-performing quad-core processor at the same frequency. These results, as well as the latest benchmark tests, based on AMD Opteron Model 2222 and 8222 SE processors can be found at www.amd.com/opteronperformance.

"Today's announcement further demonstrates AMD's commitment to delivering excellence and represents continued innovation along the customer-directed path we blazed four years ago; we provide the complete x86 processor architectural standard others in the industry are trying to emulate and we have planned a seamless upgrade path to native quad-core for delivery to the market in mid-year," said Randy Allen, corporate vice president, Server and Workstation Business, AMD. "With our native quad-core technology, AMD continues to build off of a consistent architecture and will deliver more than just four processing cores. We believe our enhanced architecture will deliver increased performance and performance-per-watt without forcing disruptive platform transitions. Investment protection continues to be a central focus of our customer-centric design principles."

A Winning Combination
LS-DYNA® and Windows Compute Cluster Server 2003 (CCS)

Trent Eggleston, FEA Information Inc.

Excerpts from Reducing the Complexity of HPC for Simulations
The complete article can be located on line in pdf format

Calculating computationally intensive problems on a single CPU can take hours, days, or even weeks. Performing the same calculations in parallel by using cluster technology increases processing speed dramatically, and can save a project valuable turnaround time.

Windows Compute Cluster server 2003 (CCS) is a high-performance computing (HPC) platform that uses clusters of industry-standard 64-bit computers. It is simple to deploy and operate, allowing engineers and scientists to focus on the science, and not the IT.

The LS-DYNA® suite and Microsoft Windows Compute Cluster Server 2003 accelerate calculations speed and reduce time to insight for a wide range of industries and applications. CCS provides a powerful platform for HPC, while LS-DYNA provides flexible simulation solution for finite element analysis. Together, users receive a simple to sue, cost-effective, and robust parallel processing solution for the simulation of product testing and design that would otherwise require large system and IT resources.

LS-DYNA combined with Microsoft Windows Compute Cluster Server's high-performance computing platform provides an accelerated solution for engineers, mathematicians, and designers in may industries.

For More Information about Windows Computer Cluster Server 2003:

Full Pdf: Reducing the Complexity of HPC for Simulations

LS-DYNA Featured AVI

Complete AVI's can be viewed at:

www.feainformation.com – top bar link "AVI Lib"

92 **988KB**
Fluid flow between containers, with a floating object

92a **477Kb**
Fluid flow between containers, with a floating object

AVI's are courtesy of G. Nilakantan U of Cincinnati

carhs.training gmbh

Managing Director: Rainer Hoffmann
rainer.Hoffmann@carhs.de

carhs.training Seminars and Events in Automotive Safety in summer 2007

All seminars are available as in-house seminars in English!

2007

12.-13. June	Seminar+Workshop Pedestrian Protection in Bergisch-Gladbach (in German)	different trainers in coopera-tion with BGS
14. June	Vehicle homologation in Alzenau (in German)	Wolfgang Wister, Magna-Steyr
19.-20. June	Simulation of plastics and foam for crash simulation in Alzenau (in German)	Paul du Bois
21.-22. June	Objective measurement of seating comfort in Alzenau (in German)	Steffen Adler, Dr. Arnd Frie-drichs, LWS Consulting
9.-10.July	Design of Experiments in Alzenau (in German)	Dr. Karl Siebertz, Ford
27.-28.June	Introduction to passive safety of vehicles in München (in German)	Dr. Alois Mauthofer, carhs.communication gmbh
25.-26. Sept.	Grazer SafetyUpDate in Graz, Aus-tria - **New Date!** (in German and English)	different trainers in coopera-tion with VSI/Prof. Steffan

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LS-PrePost® Online Documentation News

www.lstc.com/lspp

23-Apr - Added an updated User Guide and set of Examples for the BlockM Interface

19-Mar - Tutorial 17 added to online documentation (Intro to MetalForming Interface)

Free Demo License of LS-DYNA, LS-Pre-Post and LS-OPT

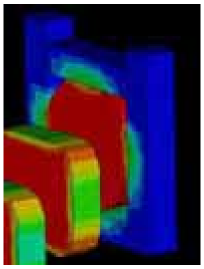
LS-PrePost® was designed to provide the following core functionalities:

- Full LS-DYNA® keyword support
- LS-DYNA model visualization
- LS-DYNA model creation and editing
- Advanced post-processing

LS-PrePost's main post-processing capabilities include states result animation, fringe component plotting, and XY history plotting.

LS-PrePost is also capable of importing and exporting data in a number of common formats. The figure on the right illustrates a sampling of those that a typical user might find most useful.

LSTC California & Michigan Training Classes
May – June - July



A complete list of dates can be found on the LSTC website

May		
01-04	CA	Introduction to LS-DYNA
June		
05-08	MI	Introduction to LS-DYNA
12-13	CA	Contact
14-15	CA	Composite Materials
18-19	CA	Material Modeling Using User Defined Options
26-29	CA	Advanced – Impact Analysis
July		
11-13	CA	Ale/Eulerian & Fluid/Structure Interaction
30-Aug 02	CA	Introduction to LS-DYNA

For Class Details:
www.lstc.com

Participant Benchmarks On TopCrunch.

TopCrunch.org For Complete Vendor Submitted Benchmarks

Linux Networx/Scali, Inc. – March 21

Computer/ Interconnect	Processor	#Nodes x #Processors per Node x #Cores Per Processor = Total #CPU	Time (sec)	Benchmark Problem
LS-P/Infiniband SDR	Intel Xeon 5160 3.0GHz	8 x 2 x 2 = **32**	551	neon_refined_revised
LS-P/Infiniband SDR	Intel Xeon 5160 3.0GHz	8 x 2 x 1 = **16**	608	neon_refined_revised
LS-P/Infiniband SDR	Intel Xeon 5160 3.0GHz	4 x 2 x 2 = **16**	811	neon_refined_revised
LS-P/Infiniband SDR	Intel Xeon 5160 3.0GHz	4 x 2 x 1 = **8**	1127	neon_refined_revised
LS-P/Infiniband SDR	Intel Xeon 5160 3.0GHz	2 x 2 x 2 = **8**	1499	neon_refined_revised
LS-P/Infiniband SDR	Intel Xeon 5160 3.0GHz	2 x 2 x 1 = **4**	2172	neon_refined_revised
LS-P/Infiniband SDR	Intel Xeon 5160 3.0GHz	1 x 2 x 2 = **4**	2885	neon_refined_revised
LS-P/Infiniband SDR	Intel Xeon 5160 3.0GHz	1 x 2 x 1 = **2**	4212	neon_refined_revised

Participant Benchmarks On TopCrunch.

TopCrunch.org For Complete Vendor Submitted Benchmarks

Fujitsu Siemens/CETMA Consortium – March 27-29

Computer/ Interconnect	Processor	#Nodes x #Processors per Node x #Cores Per Processor = Total #CPU	Time (sec)	Benchmark Problem
Workstation Celsius V830/*Information Not Provided*	Opteron 250 2400MHz	1 x 2 x 1 = **2**	7734	neon_refined
Workst.Celsius V830 CETMA/*Information Not Provided*	Opteron 250 2400MHz	1 x 2 x 1 = **2**	7734	neon_refined_revised
Workstation Celsius V830/*Information Not Provided*	Opteron 250 2400MHz	1 x 2 x 1 = **2**	7918	neon_refined_revised
Celsius M430 Pent.4 CETMA/*Information Not Provided*	Pentium4 530, 3GHz	1 x 1 x 2 = **2**	29720	neon_refined_revised
Workst.Celsius V830 CETMA/*Information Not Provided*	Opteron 250 2400MHz	1 x 1 x 1 = **1**	15551	neon_refined_revised
Celsius M430 Pent.4 CETMA/*Information Not Provided*	Pentium4 530, 3GHz	1 x 1 x 1 = **1**	32629	neon_refined_revised

2007 Worldwide Events

LS-DYNA Events

DATE	Country	Conference	Hosted By:
May 29-30	Sweden	6th European LS-DYNA Conference	ERAB
Oct 11-12	Germany	LS-DYNA Users Meeting, hosted	DYNA*more*
Oct 30-31	Japan	Japan LS-DYNA Users Conference	JRI-SOL

The 8th International Users Conference 2008 will again be held in Dearborn, MI, USA – Conference Website

Events

DATE	Country	Conference
June 01-08	UK	Int'l Conferenc on Computational Ballistics
June 12-13	German	VAUC 2007 – Vibro-Acoustic User Conference
July 02-04	Russia	Computational Methods and Experimental Measurements
July 23-26	USA	Ninth US National Congress on Computational Mechanics
Sept 17-19		Annual Technical Conferencs of the American Society for Composites

India Participant News
ETA And Cranes Software International Limited

Exceprt from Press Release:

Cranes Software the Bangalore based Global Scientific and Engineering Software Products and Solutions Company has concluded an agreement with Engineering Technology Associates (ETA) of USA, to distribute and support LSTC's LS-DYNA™ and ETA's eta/VPG™ & eta/DYNAFORM™ products across India.

Workshops and product demonstrations to increase the awareness, as well as educating the user base of LS-DYNA, eta/DYNAFORM and eta/VPG. LS-DYNA will be held in India.

About Cranes:
Full information can be found at Cranes Software International Limited

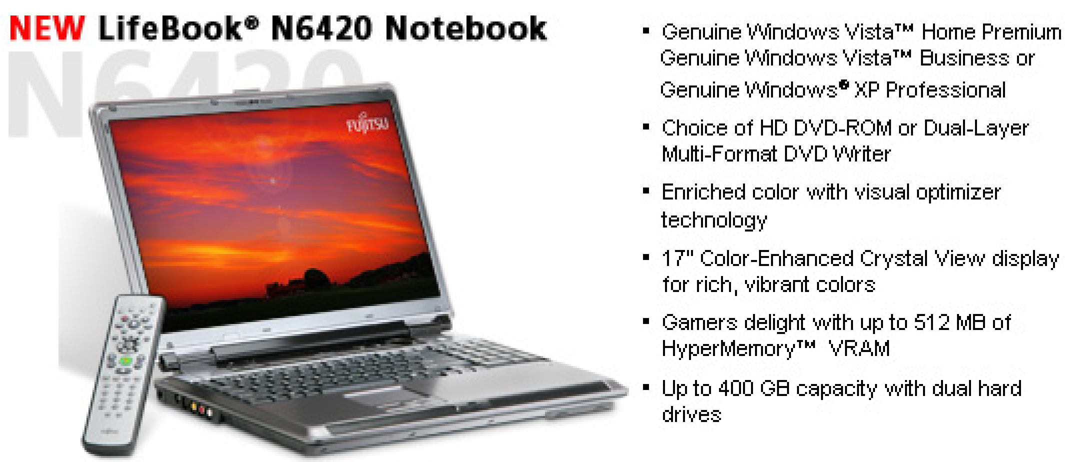
Technological progress can largely be credited to the dedicated efforts of scientists and engineers worldwide whose accumulation and inventive application of knowledge has created immense intellectual assets from which we all benefit everyday. Therefore, it is imperative to provide our scientists and engineers with an environment that is conducive to their innovative pursuits

At Cranes Software, we have dedicated ourselves to this cause, either by providing proprietary solutions or by partnering with leaders in this field. We have developed software tools, specifically designed for scientists and engineers enabling them to discover and build, invent and innovate newer technologies. We have also created a robust pipeline that can reach the global technical community with effectiveness and impact. This has been made possible by leveraging our deep domain knowledge of this niche market

Today, Cranes Software International Ltd. is a global corporation offering scientific and engineering products and solutions to clients worldwide. The Company has its presence in 39 countries across the world and has a customer base of more than 350,000

Distribution of ETA Products and LS-DYNA:

“...Mr. Pradeep Kumar, Executive Vice President of Cranes Software comments, "Our association with ETA will enhance our product portfolio especially for the transportation industry. eta/VPG in combination with LS-DYNA will help our customers handle explicit dynamic analysis problems like crash, impact, safety and drop tests which are of critical importance in today's transportation and consumer electronics industry, and will complement Cranes' general-purpose FEA package NISA. With eta/DYNAFORM, Cranes will enter the manufacturing sector with a world-class metal forming solution especially addressing die and stamping analyses needs. This strategic alliance, with synergies in products, services, and customer profiles, will better serve our clients with greater product breadth and depth…."



LifeBook E Series notebook	LifeBook T3000 Notebook
Fujitsu LifeBook T4215 Notebook	New Fujitsu LifeBook® Q Series Notebook PC
New Fujitsu LifeBook® T4210 Tablet PC	New Fujitsu LifeBook® S7110 Notebook
New Fujitsu LifeBook® E8210 Notebook	New Fujitsu LifeBook® N3530 Notebook

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iomega

Love your Zip Drive? Try a new high capacity Iomega REV 35GB Drive.
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The Iomega Super DVD Burner Dual-Format USB 2.0 external drive. Buy now and SAVE!
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is your one stop source to find any Japanese products! We currently offer a wide selection of Japanese games, CD / DVDs, Electronics, and more! gdex.jp was founded in May 2006,

GDEX Inc.

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Apple Store for Education. College Students save on MacBooks and more.

The perfect fit. Find accessories designed for your iPod at the Apple Store.

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COMPUTERS4SURE

Products that Protect your Technology - Computers4SURE

2007 ANSYS U.S. Regional Conference Series: PENNSYLVANIA

May 14-16, 2007 Renaissance Philadelphia Hotel
500 Stevens Drive Philadelphia PA 19113

- Overview
- Program Highlights
- Application Deep Dives
- Training

Overview

The 2007 ANSYS U.S. Regional Conference Series: PENNSYLVANIA is an exciting convergence of people, technology and ideas. The Day 1 and Day 2 program offers a broad range of valuable content relevant for ANSYS, Inc. and Fluent Inc. customers and prospective customers alike, and will include an overview of the technology roadmap, updates on new product features and product integrations, a management roundtable, customer presentations and demonstrations.

Special content for chemical and material processing, government/defense, energy, and general industries will include user presentations and demonstrations as described below.

Day 3 offers post-event advanced training that will boost your productivity and help you effectively apply ANSYS®, ANSYS® CFX™ and FLUENT® solutions to solve your engineering problems.

This conference is a must-attend event for product development professionals - from engineers to decision-makers - who want to learn how to accelerate innovation, improve quality, reduce costs and get products to market more quickly.

Program Highlights

- keynote presentation by Dr. Fadim Sadek of the National Institute of Standards and Technology. Dr. Sadek will discuss the project “Baseline Structural Performance and Aircraft Impact Damage Prediction” which was part of the NIST investigation into the collapse of the World Trade Center buildings.

- get an insider's look at the entire ANSYS and Fluent product portfolio, including the technology roadmap

- find out how the latest enhancements in ANSYS 11.0, ANSYS CFX 11.0, FLUENT 6.3, and ANSYS® ICEM™ CFD 11.0 can improve your organization's product development efforts
- learn how the integration of ANSYS and FLUENT capabilities within the ANSYS portfolio of products/services can accelerate innovation and reduce time-to-market
- The Need for Speed: a management roundtable providing the opportunity to exchange ideas on accelerating innovation and winning the race against your competition.
- meet the combined ANSYS and Fluent team, including executives and staff members
- converge with our partners and technology experts in the Simulation Showcase exhibit/demo area

Application Deep Dives

Find out how users—from chemical and material processing, government/defense, energy, and general industries—are utilizing ANSYS, Inc. solutions to solve challenging problems in a variety of different applications.

Chemical Processing

- Improving Emissions From Spent Sulfuric Acid Plants – Wilford Shamlin, DuPont
- CFD Analysis for Nox-Control in Refinery - Kathleen Brown, Spraying Systems
- Modeling Aerosols for Consumer Applications – Nitin Sharma, SC Johnson
- Computational Analysis, Design and Scale-Up of Polymerization Reactors – Nitin Kolhapure, DuPont

Material Processing

- Free Surface Instability Simulation for a Viscous Liquid Flowing Down an Incline - Alex Borsa and Yi-Fang Cai, Johns Manville
- Computational Modeling for Glass Container Forming and Defect Detection - Professor Matt Hyre, Virginia Military Institute
- Profile Extrusion Validation Using POLYFLOW - Nitin Sharma, SC Johnson
- Simulation of Molding Precision Aspheric Glass Lenses - Balajee Ananthasayanam, Clemson University
- Designing Dies for Rubber Profile Seal Extrusion – Jaydeep Kulkarni, ANSYS, Inc.

- Modeling of Submerged Combustion Melting in Glass Tanks - Bruno Purnode, Owens Corning
- Modeling Material Effect on Flame Shape in an Aggregate Dryer Using Coupled CFD and DEM - Andrew Hobbs, Astec Inc.
- Jet Penetration in a Slurry Flash Vessel - Umesh Shah, Hatch Ltd

Energy Industry

- CFD Modeling as a Powerful R&D and Engineering Tool in Energy-from-Waste Power Systems – Greg Epelbaum, Covanta Energy
- CFD Contribution to Corrosion Inhibition in Oil and Gas Pipelines – Allan Runstadler, Natural Resources Canada, CANMET Materials Technology Laboratory
- Examples of CFD Applications in the Nuclear Industry - Milorad Dzodzo, Westinghouse Electric Science and Technology Department

General Industries

- Spring Loaded Fuel Cell Systems - Constantinos Minas, Ph.D., MTI MicroFuelCells Inc.
- Application of CFD Model to Indoor Air Sensor Network Design - Lisa Chen, Drexel University
- Modeling Resistance of a Mattress/Box Spring Set to a Large Open-Flame - Kevin Allred, Dupont

Government/Defense

- Supersonic Turning Vanes in Muzzle Brakes - Daniel Cler, U.S. Army Benet Laboratories
- Spent Fuel Cask Performance in Tunnel Fires – Chris Bajwa, U.S. Nuclear Regulatory Commission
- Large Eddy Simulation of Turbulent Free-Surface Flows Around Surface-Piercing Bodies - Sung-Eun Kim, Naval Surface Warfare Center
- Rotor Modeling Using a Momentum Source UDF – Charles Berezin, Sikorsky Aircraft Corporation
- Applications of ANSYS Multiphysics at NASA/Goddard Space Flight Center – Jim Loughlin, NASA Goddard Space Flight Center
- Interfacing Fire and Thermal Analyses Via Adiabatic Surface Temperatures – Dat Duthinh, National Institute of Standards and Technology
- Thermo-Mechanical Analysis of Chemical Protective Clothing System Using CFD - Thamishisai Periyaswamy, Philadelphia University

Demo Stations

- FLUENT Demonstration: Emulsification Predictions, Including Mixing Analysis and Population Balance Methods
- FLUENT for CATIA Demonstration
- POLYFLOW Demonstration: Modeling Polymer Processing (Extrusion and Thermo-forming) and Glass Forming Applications
- ANSYS Demonstration: Thermal, Transient, and Stress Analysis of a Ball Grid Array
- ANSYS Demonstration: FSI Analysis of the Structural Effects of Pressures Generated by Fluid Flow on a Missile Wing Section
- ANSYS Demonstration: What's New in ANSYS 11.0
- ANSYS AUTODYN Demonstration: Explicit Dynamics Simulation of a Parametric Projectile
- ANSYS Demonstration: Rigid and Flexible Dynamics
- ANSYS CFX Demonstration: Multiphase (Gas-Liquid) Agitated Tank with Reaction

Training

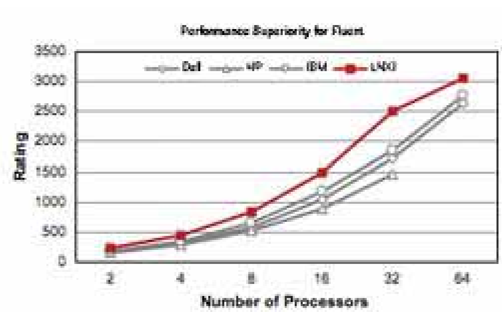
- Advanced Fluid Structure Interaction between FLUENT and Finite Element Analysis (FEA) Codes
- Fluid Structure Interaction (FSI) Using ANSYS Workbench and ANSYS CFX
- Advanced Multiphase Flow Modeling with FLUENT
- Advanced Dynamic Mesh Modeling with FLUENT

Product Spotlight

Linux Networx LS-1 Supersystems

LNXI - Linux Networx.

The LS-P Series of turnkey, production-ready systems delivers industry-leading application throughput and significant reductions in Total Cost of Ownership (TCO) for leading product design applications. LS-P systems are performance-tuned for computational fluid dynamics (CFD), crash/impact analysis and structural analysis applications. Visualization software from CEI is supported as a tuned, integrated application on all systems. In performance benchmarks, LS-P systems drive up to 50% improved performance for ISV industry applications.



LS-1 Supersystems

Linux Networx LS-1 Supersystems deliver the ultimate tuned computational performance and work throughput in the supercomputing industry. With greater computational power and design flexibility, lower operational and management costs, and reduced system complexity, the LS-1 delivers superior Linux Networx price/performance value to every customer.

LS-1 Supersystems are available in standard configurations featuring proven hardware and software components. Our system architects and application specialists tune every LS-1 to achieve the highest application performance for industry applications, custom codes and client workloads. Because of our superior design, configuration, and tuning capabilities, the LS-1 readily surpasses the computational power and technological flexibility of first generation clusters while eliminating their legacy costs of ownership and burdensome complexity.

The comprehensive design and integration of the LS-1 delivers the lowest possible Total Cost of Ownership (TCO). Every LS-1 Supersystem is validated, integrated, and burned-in before delivery, and arrives at the customer site ready for “Production at Power Up.”

Our industry-leading system management suite delivers superior productivity and ease-of-use with its advanced administration capabilities. All LS-1 Linux Supercomputers can be fully integrated with a comprehensive array of industry-leading data storage solutions and a complete range of high-performance parallel file systems to maximize performance throughput. Linux Networx supercomputing visualization capabilities can be seamlessly incorporated into every LS-1 Supersystem.

LS-1 Supersystems are designed and optimized to deliver:

- **Tuned Supercomputing -** Every LS-1 Supersystem configuration is specifically tuned by Linux Networx application experts working with our application partners to deliver unrivaled Total Application Throughput. The ability to configure and optimize the LS-1 for specific industry codes and workflows maximizes the amount of real-world work realized by the user.

- **Power without Complexity -** The LS-1 is a fully integrated and tuned supercomputing system unifying the most advanced processors, memory, interconnects and software available, and can be complemented with high performance data storage and visualization subsystems. The result of this total integration is Linux Supersystem computational power with the benefits of a standardized systems experience.

Production at Power Up – All LS-1 Supercomputers are completely validated and integrated supercomputing systems, including hardware, operating system, applications, libraries, and tools. Engineered from the ground up to quickly deploy and power-up, the LS-1 delivers rapid time-to-productivity for users and applications. Customers can immediately apply the LS-1’s computational power to their research and design challenges, not on system set-up and implementation.

FROM FEA TO MCAE TODAY – A 40-YEAR PERSONAL ODYSSEY

Henry H. Fong
San Francisco, California
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Part 1. Beginnings (1950s-1960s)

1.1 Introduction

I'm a lucky fellow. Lucky in the sense that at the beginning of my 40-year career, I witnessed the golden age of finite element method (FEM) research, and the subsequent development of commercial finite element analysis (FEA) codes in the 1970s and 1980s. In my career, I have applied FEA codes in the structural integrity assessment of many interesting aerospace structures and components – launch vehicles and missiles, spacecraft, solar energy heliostats, rocket nozzles, and traveling wave tubes. *The finite element method is an approximate numerical analysis technique to solve a wide variety of engineering problems.*

The immense technical advances and increasingly widespread use of FEA coincided with the exponential increase in computer power in the past 40 years. We have moved in this period from multi-million dollar mainframes and supercomputers (usually placed in restricted-access, air-conditioned, machine rooms with raised floors – guarded zealously by IT geeks whose first priority was to run business applications) to the affordable desktop PCs/workstations and laptops available today.

I came to the U.S. in 1956 as a teenager, and graduated from Lowell High School in San Francisco. I then enrolled at the University of California at Berkeley, majoring in civil engineering. In my freshman year, I took an "engineering measurements" course, where my teaching assistant was a friendly graduate student named Bob Taylor. Then, in my junior year, Bob had just received his Ph.D degree, and was my instructor in strength of materials. After obtaining my B.S., I proceeded onto graduate school at Berkeley, took a solid mechanics course from Bob, and then did my M.S. research project with him. Bob told me that in the mid-1960s, things were getting "pretty exciting" in a new field called finite elements, and that there were many challenging research opportunities in this field. He had a twinkle in his eyes, like a kid who was going on his first roller coaster ride with a carton of cotton candy.

This article is a 3-part survey paper on my 40-year career in FEA/MCAE (mechanical computer-aided engineering). It reflects my own FEA user experiences (working at four Southern California aerospace companies for 14 years), and then, doing customer support, training, documentation, and technical marketing for another 14 years at two MCAE software developers (PDA Engineering, MARC Analysis). Finally, for the past 12 years, I was involved in Manufacturing Industries business development and worldwide sales support, for high performance computing (HPC) hardware platforms that run MCAE applications. As such, this article neither pretends to be authoritative nor complete, and I hereby apologize for any unintentional omissions of someone's name or FEM/FEA contribution. The interested reader who may be unfamiliar with FEA is referred to the *Bibliography*, which contains a selected list of FEM textbooks and technical articles.

Part 1 of the article gives a brief historical sketch (1950s-1960s) of the finite element method, and the contributions of some early researchers – most of whom were engineers. In the late 1960s to early 1970s, applied mathematicians finally validated the FEM approach, put the method on firm mathematical foundations, and proved its convergence and accuracy.

Part 2 – Development of Commercial FEA Codes (1970s-1980s) describes the first generation of commercial FEA codes (e.g., STARDYNE, NASTRAN, ANSYS, MARC, ASKA, etc.) and pre- and postprocessors (SDRC/SUPERTAB and PDA/PATRAN). The MacNeal-Schwendler Corporation, developer of the MSC/NASTRAN FEA code for structural and dynamic analyses, was the first FEA software vendor to go public. All of a sudden, Wall Street heard the terms FEA and MCAE for the first time, and FEA/MCAE was no longer a "cottage industry."

The development of the DEC VAX 11/780 minicomputer in 1977 made it feasible to develop interactive graphics used in the pre- and postprocessors. Instead of doing a "batch submit" of the FEA job in a box of punch cards (. . a major disaster if the box was dropped), the user could now do an "interactive submit," construct and see and modify the model in real time, for instance, on a Tektronix graphics terminal. The user could also visualize the results after the finite element analysis, and interactively make improvements to the model if needed.

Researchers also started to realize, beginning in the 1960s, that FEM could be extended from its structural analysis roots to solve other problems in heat transfer, fluid mechanics, electromagnetism, geomechanics, acoustics, and biomechanics.

Also mentioned in Part 2 are some FEA/MCAE conferences which were organized for code developers, researchers, and end users to learn about the latest FEM developments. These included: the three Wright-Patterson Air Force Base *Matrix Methods in Structural Mechanics* conferences held in 1965, 1968, and 1971; the Chautauqua's organized by Dr. Harry G. Schaeffer; AIAA/ASME/ASCE/AHS Structures, Structural Dynamics, and Materials conferences; Dr. John Robinson's World Congresses of Finite Element Methods; and worldwide conferences organized by the UK-based National Agency for Finite Elements Method and Standards (NAFEMS). Each FEA code developer, of course, also held its own user conferences, usually once a year.

Part 3 – Maturing of FEA/MCAE (1990s to Today) discusses the maturing of the FEA/MCAE industry in the past two decades. The PC made FEA computing affordable and personal; the FEA engineer was finally liberated, and no longer had to fear the IT geek. A brief overview is given of the MCAD industry. Current MCAD market leaders (Dassault Systemes/CATIA, Unigraphics) have been recently gobbling up FEA/MCAE vendors, in order to offer their customers "one stop shopping." Some recent mergers and acquisitions are mentioned, confirming the shakeout and consolidation going on in MCAD/MCAE. New and powerful graphics chips (e.g., Nvidia and ATI), driven by the game industry, have also made an impact on the FEA/MCAE workplace.

Linux, the open-source operating system created by Linus Torvalds, has become a significant trend on computing worldwide, including MCAE and other HPC markets (e.g., life sciences – genomics, proteomics, and big pharma, energy, and Wall Street). It has become the OS of choice for many HPC/MCAE customers, who purchase clusters primarily for price/performance reasons. This led to the emergence of two new Linux OS vendors – Red Hat and SuSE.

Recent hardware innovations are surveyed: the current battle between Intel vs. AMD Opteron; product transitions from single-core processors to dual-core, and soon, quad-core; and, clusters – commonly using Linux or Unix OS's with medium- and high-speed interconnects offered by vendors such as: Myricom/Myrinet, Scali, and Infinband vendors

Cisco/Topspin, Voltaire, and QLogic/Silverstorm. Recent 2006 Q4 HPC server market share and revenue growth (according to IDC and Gartner estimates) are reviewed, comparing IBM, HP, and Sun. The scalability (with increasing processor count) of various MCAE explicit transient codes (e.g., LS-DYNA for crash) and CFD codes (e.g., FLUENT, STAR-CD) is discussed.

Finally, some challenges and trends in MCAE today and in the future are discussed – e.g., training and technical support issues in a 24x7 world; software distribution using the Internet (vis-a-vis Google) instead of shipping CD's by FedEx or UPS; the mentoring of new engineers when the older, experienced FEA analysts retire and pass on; Grid Computing – a useful concept, but still struggling to become mainstream; the emergence of China and India in this decade as worldwide manufacturing and outsourcing powerhouses; continued absence of standards for nonlinear FEA; and over-reliance of U.S. manufacturing and hi-tech industries on foreign-born, U.S.-trained engineers – what if they decide to go home to China or India to seek better job opportunities?

Professor Bob Taylor retired in 1994 after a distinguished teaching and FEM research career at UC Berkeley, and since then, he is a Professor in the Graduate School. In 1991, he was elected to the National Academy of Engineering, a peer-elected academy (2,405 members) of engineers who have made outstanding contributions to the engineering profession. Bob and I had kept in touch and remained friends over the past 47 years; he was always curious in how I was doing, and what interesting projects I was working on. Through Bob, I was introduced to four distinguished FEM researchers: Professors Olek Zienkiewicz, Tinsley Oden, Tom Hughes, and Juan Simo. I fondly remember Olek, Bob, my wife Evelyn and I enjoying a great seafood lunch by the beautiful Barcelona harbor, on one lazy, sunny afternoon in 2002. After lunch, Olek kindly offered to drive us back to our hotel. Bob acted as the backseat driver, shouting directions to Olek – who had impaired vision *and* hearing, in addition to being a rather poor driver and terribly confused by Barcelona's meandering streets. (Evelyn and I were glad to get out of Olek's car!) I dedicate this article to Bob Taylor – my teacher, mentor, and life-long friend.

1.2 Beginnings of FEM / FEA

In the beginning, there was the triangle. The first "commercial" finite element was a triangular element used for analyzing plane stress problems in Boeing airplanes (see the seminal 1956 paper by Turner, Clough, Martin, and Topp in the *Bibliography*). This paper described the development of a (linear) triangular element, based on virtual work principles. Such an approach became the basis of what was later named the "Matrix Displacement Method" or "Direct Stiffness Method," since the nodal unknowns are *displacements* or deflections, and the solution of the numerical problem involves an inversion of the stiffness matrix. It was also known that in 1943, the eminent mathematician Richard Courant had used an assembly of triangular elements, and the principle of minimum potential energy, to solve the St. Venant torsion problem. Professor Ray Clough at UC Berkeley was the first to coin the term "finite element method," in his classical 1960 ASCE paper on solving plane-stress civil engineering problems (Clough, 1960).

Around the same time, in England, Professor John H. Argyris published in *Aircraft Engineering* a famous series of articles on numerical analysis of structural mechanics (Argyris, 1954-55), which were later collected and re-published, with S. Kelsey as co-author, a monograph entitled *Energy Theorems and Structural Mechanics* (Argyris and Kelsey, 1960).

These two trail-blazing articles in the mid-1950s by Argyris (1954-55) and Turner, Clough, Martin and Topp (1956) are considered to be the “foundation papers” for the Finite Element Method (specifically, the Displacement Method). Starting in the 1960s, Professor O.C. Zienkiewicz and his colleagues at University of Swansea in Wales initiated a series of FEM research projects, primarily aimed at extending FEM from structural analysis to solve other field problems (see the texts by Zienkiewicz and Taylor, 1989, 1991, 2005). Professor Robert L. Taylor from UC Berkeley spent three sabbatical leaves at Swansea, and this rich collaboration between Taylor and Zienkiewicz’s group led to many outstanding FEM papers and Ph.D theses at Swansea. Professor Argyris then moved from UK to head the Institut fur Statik und Dynamik (ISD) in Stuttgart, Germany, and assembled an impressive German FEM research group there. Amongst their many notable FEM achievements, the ISD research team developed the theoretical bases for the linear/nonlinear FEA code ASKA – which I used at Rockwell International in 1977 to perform nonlinear FEA of the carbon-carbon tiles (which undergo extremely high temperatures during reentry), that made up the Space Shuttle thermal protection system.

Someone once estimated that these three preeminent FEM research centers – UC Berkeley (Ray Clough, Bob Taylor, Ed Wilson, et al), University of Swansea (Olek Zienkiewicz, et al), and ISD Stuttgart (John Argyris, et al) – accounted in the 1960s-1980s for something like *half* of all the most outstanding FEM research achievements (and FEM Ph.D degrees awarded) in the entire world!

Meanwhile, at Douglas Aircraft Co. in Long Beach, California, Paul Denke and his Stress Group colleagues had developed during the 1960s-1970s a different *Matrix Force Method* computer program, to analyze Douglas jets such as the DC-8, DC-9, DC-10, C-130, and MD-11 (Denke, 1968). Instead of using nodal displacements as the unknowns, the Force Method uses nodal forces. An innovative scheme is used to automatically “cut” the structure into substructures. The “flexibility matrix” is solved, instead of the stiffness matrix used in the Displacement Method.

Denke and his colleagues validated the method by successfully correlating their results with many test results. Although Argyris had also established the validity of the Force Method in his 1954-55 papers, the Displacement (Stiffness) Method gradually won out over time, and became the *de facto* standard Finite Element Method. This happened for a variety of reasons: real-world complex structures and components were easier to model; and computer programming was easier. And politically, the NASA-sponsored NASTRAN program (Jones and Fong, 1981, 1982) became the aerospace industry-standard FEA code starting in the early 1970s. NASTRAN also rapidly became the dominant NVH (noise, vibration, and harshness) code used in the worldwide automotive industry. Douglas Aircraft Co. (later McDonnell Douglas, now part of Boeing) was, as far as I know, the only major manufacturer using a Force Method finite element code.

The *Finite Difference Method (FDM)* gives a *pointwise* approximation to the governing equations — as opposed to FEM’s idealizing a region as many small, interconnected subregions or elements and giving a *piecewise* approximation. FDM was popular in the 1940s and 1950s – especially in CFD codes used to simulate laminar and turbulent flows around aircraft fuselage, tails, and wings. In FDM, the model is formed by writing difference equations for an array of grid points. Engineers, however, found the FEM codes easier to use than FDM codes, especially to model complex, irregular boundaries in the structure, and also when they encountered an unusual specification of boundary conditions.

Another numerical analysis scheme developed was the *Boundary Element Method* (C.A. Brebbia, F. J. Rizzo, et al). This method utilizes Green's theorem to reduce the dimensionality of the problem – a volume problem is reduced to a surface problem, a surface problem is reduced to a line problem. The method is computationally less efficient than FEM, and is therefore not widely used in industry. However, it is popular for acoustics, and is also used in analyzing electromagnetics and geomechanics problems.

In the past 40 years, FEA has become ubiquitous, worldwide, and mind-boggling as to its vast array of innovative applications. Using FEA codes has enabled manufacturers to develop safer and better products faster, optimize use of materials, minimize weight – and thus gain a competitive edge. You can bet that virtually any product you see, touch, or use today most likely have been designed using FEA – an airplane, car, truck, windshield, locomotive engine, satellite, or a Herman Miller ergonomically-designed chair, jet engine, dam, car fender, electric shaver, or a light bulb, golf club, golf ball, violin, tooth implant, a stent for a cardiovascular surgeon to pry open a artery clogged with plaque, or a Zimmer artificial "Gender Knee" specifically customized for women (using ABAQUS and ANSYS for FEA, and currently advertised on TV). FEA usage started in the aircraft/aerospace industries, moved quickly to the automotive and nuclear industries, and has now spread to virtually all industries – such as consumer goods, electronics, heavy equipment, machinery, chemical, and big pharma.

A Google search today on the two keywords "finite element" yielded 36.0 million hits! For keywords "finite element method": 19.3 million hits; for "finite element analysis": 20.9 million hits. A Google book search today using the keywords "finite element method" showed a total of 2,575 books – a tremendous increase over one FEM textbook in 1967 (O.C. Zienkiewicz and Y.K. Cheung's *The Finite Element Method in Engineering Science*), 10 books in 1974, 40 in 1982, and 400 in 1991 (Noor, 1991).

1.3 Validation of FEM

But wait a minute, the finite element method was developed by engineers! In their 1956 paper, Turner and Topp were research engineers from Boeing, Harold Martin was an aerospace engineering professor at University of Washington, and Ray Clough was a civil engineering professor at UC Berkeley. How do we know the method they developed and their FEA results were correct? Was it safe to fly a 707, 727, 737, or a 747?

It remained for two MIT applied mathematicians, Professors Gilbert Strang and George Fix, to validate the finite element method, give the method a firmer mathematical foundation, and prove mathematically and rigorously that with increased mesh density, the predicted FEA results indeed converged (Strang and Fix, 1973). They also examined and estimated discretization error, rates of convergence, and stability for different types of finite element approximations.

A third individual should be mentioned: Bruce Irons. Irons was an outstanding UK FEM researcher who made key contributions to the development of isoparametric elements (see any FEM text on *isoparametric elements* and on *the patch test*). He attributed the widely used 2D, 5-quad element, "picture window" *patch test* (which tests convergence for a plane problem) to John Robinson. They stipulated that any 2D finite element, for example a plane-stress quadrilateral element, must pass the patch test in order to converge. With a point load at a corner node, the patch test states that the stresses in all five quadrilateral elements in the "picture window" patch test model must be the same. The patch test also comes in 3D – a 7- brick element model with a small cube inside a larger cube. The patch test was controversial, stirring up heated debate amongst finite element researchers and mathematicians in the 1970s. Eventually, the furor wound down, and the FEM community accepted it as a valid test for convergence.

Part 2. Development of Commercial FEA Codes (1970s-1980s)

Part 2 covers the development of the first commercial FEA codes in the early 1970s, CFD codes, and pre- and postprocessors. Then, the development of 2nd generation FEA codes is described (towards the end of the 1970s and 1980s), along with crash codes, more CFD codes and pre- and postprocessors, and FEA codes in some other technical disciplines – electromagnetics, injection molding, and design optimization. A materials database is described. The historical development of the early CAD (MCAD) codes is summarized. Rapid hardware advances in these two decades are then highlighted. Some well-known FEA/MCAE conferences held in the 1970s and 1980s are cited. Part 2 closes with an interesting FEA anecdote from my career. [Note: Many other FEA codes are not described here, due to lack of space, e.g.: SRAC/COSMOS – later acquired by Dassault Systemes; RASNA – acquired by PTC and renamed Pro/MECHANICA (but seems to have disappeared from the scene); ALGOR; NISA; Honeywell/EPIC; the explicit dynamics code Physics International/PISCES – which later morphed into MSC.Dytran; the explicit code Century Dynamics/AUTODYNE – which was acquired by ANSYS, Inc. in 2005; SAP-IV; NE/NASTRAN; Mecalog/RADIOSS; the SYSNOISE acoustics code and the DADS kinematics code from LMS International (Leuven, Belgium); etc.]

2.1 Origins

MRI/STARDYNE – Mechanics Research, Inc. was the developer of STARDYNE, the first general-purpose, commercial linear FEA code for structural and dynamic analyses. It came out in the late 1960s. MRI (Los Angeles, CA) was founded by Dr. Richard Rosen et al. Many of MRI's staff members had obtained their Ph.D and M.S. degrees at UCLA, under Professors Walter Hurty and Moshe Rubinstein – who were well-known in structural dynamics and matrix methods of structural analysis. STARDYNE's special strengths were in structural dynamics and earthquake engineering, and to this day, there are some customers worldwide who still use this code for these simulations.

NASTRAN – The **NA**sa **STR**uctural **AN**alysis general-purpose FEA code was developed starting in the late 1960s. The aim, organization, content, and format (e.g., DMAP) of NASTRAN were established by a steering group, ably chaired by Dr. Tom Butler of NASA Goddard (sometimes called "the father of NASTRAN.") This steering group had several prominent aerospace FEM pioneers, such as Dr. Richard H. Gallagher (Bell Helicopters – later President of Worcester Polytechnic Institute and then, Dean, University of Arizona) and Dr. Robert J. Melosh (Philco-Ford – later MARC Analysis and Duke University). NASA awarded the development and support contract to The MacNeal-Schwendler Corporation (MSC) and Computer Sciences Corporation. In 1982, MSC's management (co-founder Dr. Richard H. MacNeal et al) obtained the rights from NASA to market its own enhanced version of NASTRAN, named **MSC/NASTRAN**. Subsequent versions of the government's public-domain NASTRAN FEA code then became known as **COSMIC/NASTRAN** (see Jones and Fong, 1981, 1982, for results of an evaluation in 1979-80 of this code, funded by the Office of Naval Research, with the contract monitored by Drs. Nick Perrone and Bob E. Nickell). In the late 1970s and 1980s, several other smaller NASTRAN competitors emerged, such as **CSA/NASTRAN** from CSAR Corp. (Dr. R. Narayanaswami) and **UAI/NASTRAN** from

Universal Analytics, Inc. (Drs. Tony Capelli, M. Jeff Morgan, and Eric Field). MSC went public in 1983, the first FEA/MCAE vendor to do so. In 1999, MSC renamed itself as MSC.Software Corporation (Santa Ana, CA) and renamed the code **MSC.Nastran**, and acquired CSAR and UAI – in addition to its previous acquisitions of Aries, PDA Engineering (developer of the PDA/PATRAN pre- and postprocessor, now named **MSC.Patran**) in 1994, MARC Analysis Research Corporation (developer of the MARC nonlinear FEA code, now named **MSC.Marc**), also in 1999, and in 2002, Mechanical Dynamics Inc. (developer of the ADAMS kinematics code, now named **MSC.Adams)**. [www.mscsoftware.com]

SASI/ANSYS – In 1970, Dr. John A. Swanson founded Swanson Analysis Systems, Inc., developer of the ANSYS general-purpose FEA code. He had previously worked at Westinghouse Electric Corporation. Swanson later sold a large share of his SASI ownership to TA Associates, which changed the company name to ANSYS, Inc. and took the company public. In the past seven years, ANSYS has improved its FEA code with many enhancements, and also moved aggressively into the CFD simulation area, acquiring, in rapid succession, three leading CFD software developers: **ICEM CFD**, a pre- and postprocessor primarily for CFD codes developed by ICEM CFD Engineering (Berkeley, CA); **CFX** in UK (originally part of AEA Technologies in Harwell, UK and Waterloo, Ontario, Canada); and **Fluent**, Inc. (Lebanon, NH) – the leader in the CFD market. In the MCAE industry, ANSYS, Inc.'s (Canonsburg, PA) financial performance has been exceptionally strong in the past 5-6 years; its stock has recently been in the $40s-50s – the best amongst public FEA/MCAE software vendors. President/CEO Jim E. Cashman heads the new ANSYS management team responsible for ANSYS Inc.'s financial success and drive into CFD markets. [www.ansys.com]

MARC – Like MSC and SASI, MARC Analysis Research Corporation was also founded around the same time (1972) by Dr. Pedro V. Marcal, a professor of mechanical engineering at Brown University in Providence, R.I. MARC was the first commercial nonlinear FEA code (released in 1972), and its initial customers primarily came from the nuclear industry. Marcal moved the office from Providence to Palo Alto CA in the late 1970s. MARC Analysis was acquired by MSC.Software Corp. in 1999. [www.mscsoftware.com]

ASKA – The ASKA linear/nonlinear code was developed by Dr. John H. Argyris and his colleagues at Institut fur Statik und Dynamik (ISD) in Stuttgart, Germany. This code has a wealth of capabilities, is mainly used in Europe, and the only major American ASKA customer (which I am aware of) is Rockwell International (Downey, CA), which used ASKA for the linear/nonlinear structural analyses of the Space Shuttle and its components, including its Thermal Protection System carbon-carbon tiles.

FDI/FIDAP – Fluid Dynamics International**,** co-founded by Drs. Michael S. Engelman and Simon Rosenblat, was the developer of the **FIDAP** CFD code, and the **ICEPAK** specialty code for analyzing thermal fields in electronics packaging (it competes against market leader Flomerics/**FLOTHERM**). Unlike the FEA structural codes, FIDAP and most other CFD codes solve the Navier-Stokes governing partial differential equations. After the 1996 acquisition of FDI by Fluent, Inc., Engelman left to become the CEO of a spin-off customized CAE solutions provider named Enductive Solutions, Inc.
[www.ansys.com], [www.enductive.com]

FLUENT – Fluent, Inc. (Lebanon, NH), was co-founded by Dr. Bart Patel (Creare, Inc.) and Professor Ferit Boysan (University of Sheffield, UK). Fluent, Inc. acquired **Polyflow** S.A. in 1997, after it acquired FDI in 1996. Fluent itself became a wholly owned subsidiary of ANSYS, Inc. in May 2006, and Dr. Ferit Boysan is currently VP in charge of the CFD business unit at ANSYS, Inc. [www.ansys.com]

CD adapco Group/STAR-CD – The original software developer of the STAR-CD CFD code was Computational Dynamics Ltd. in London, UK, with Professor David Gosling of Imperial College serving as a consultant. Then, CD merged with adapco, Inc. (a CAE services provider and software developer in Melville, Long Island, NY), forming the CD adapco Group, with P. Steve McDonald serving as its president. [www.cd-adapco.com]

2.2 Pre- and Postprocessors

SDRC/SUPERTAB – Structural Dynamics Research Corporation (Milford, Ohio) developed the first commercial pre- and postprocessor, **SUPERTAB**, in 1977. Many of its management and technical staff were from University of Cincinnati, including co-founders Drs. Jack Lemon (who later left SDRC to found ITI - International TechneGroup Inc., also in Milford), Al Klosterman, and Wayne McClelland. SDRC's CAD/CAE offerings also included: **GEOMOD** for CAD geometry generation; and **SUPERB** for FEA. In the late 1990s, SDRC acquired Enterprise Software/**FEMAP**, a Windows-native, stand-alone pre- and postprocessor for FEA codes. In a partnership with Control Data Corporation, SDRC developed and markets a widely used PLM code named **Metaphase**. SDRC itself was then acquired by UGS. In the past three years, UGS has launched another version of NASTRAN named **NX Nastran**, with linear and moderately nonlinear FEA capabilities. UGS first released this code in June 2004, and markets it aggressively worldwide. [www.ugs.com]

PDA/PATRAN – PDA Engineering, a composites analysis/design and CAE engineering services firm, developed the pre- and postprocessor **PATRAN** in 1978. The parametric cubic basis of PATRAN came from the PATCHES III 3D composites analysis code, which Dr. Ed L. Stanton and Lou M. Crain first developed, under U.S. Navy sponsorship, at McDonnell Douglas Astronautics Co. In the late 1970s and most of the 1980s, SDRC/SUPERTAB and PDA/PATRAN were the two most widely used FEA pre- and postprocessors in the world. PDA Engineering went public in 1984, and then was acquired by MSC.Software (Santa Ana, CA) in 1994. The product is now named **MSC.Patran**. [www.mscsoftware.com]

2.3 2^{nd}-Generation FEA Codes & Pre- and Postprocessors

HKS/ABAQUS -- The nonlinear, general-purpose FEA code ABAQUS was developed by Hibbitt, Karlsson & Sorensen, Inc., founded in early 1978. Since Drs. David Hibbitt, Bengt Karlsson, and Paul Sorensen had all worked at MARC Analysis in the 1970s, I consider ABAQUS to be actually a 2^{nd} generation nonlinear FEA code. Its first customers were in the nuclear industry. Dr. Joop C. Nagtegaal, who was a principal MARC developer in the 1980s, joined HKS in 1987. In the 1980s and 1990s, ABAQUS gradually became the standard nonlinear FEA code in the world. HKS developed its own pre- and postprocessor, **ABAQUS/CAE**. In 1991, HKS released the **ABAQUS/Explicit** dynamics code – after two Sandia Laboratories-Albuquerque FEM researchers Drs. Lee Taylor and Dennis Flanagan joined HKS (they were co-developers of the **PRONTO** explicit transient code at SLA). The original, implicit, nonlinear FEA code was renamed **ABAQUS/Standard**. In 2002, HKS renamed itself ABAQUS, Inc. (Providence, RI), and brought in Mark Goldstein from SDRC to be the President/CEO. In October 2005, ABAQUS, Inc. became a wholly owned subsidiary of Dassault Systemes – which announced a new family of analysis products under the name DS/**SIMULIA** (includes ABAQUS and CATIA FEA applications)

ADINA – This nonlinear FEA code is developed and supported by ADINA R&D, Inc. (Watertown, MA). The company was founded in 1986 by Professor Klaus-Jurgen Bathe of MIT and his associates. Since 1975, Dr. Bathe has been doing FEM research and teaching at MIT. Before that, he obtained his Ph.D at UC Berkeley, under Professor Edward L. Wilson. Wilson and Bathe jointly authored several outstanding papers and texts, and co-developed the **NONSAP** nonlinear FEA code, an extension of Wilson's original **SAP-IV** linear FEA program. ADINA is used for advanced nonlinear and thermal FEA at many worldwide manufacturers. [www.adina.com]

LSTC/LS-DYNA – The explicit transient dynamics, crashworthiness and occupant safety code LS-DYNA is developed and supported by Livermore Software Technology Corporation, founded by Dr. John O. Hallquist in 1987. Previously, at Lawrence Livermore National Laboratory (LLNL), Dr. Hallquist had developed the **DYNA3D** explicit code. He founded LSTC in order to commercialize the original technology in DYNA3D, and to transform a weapons design FEA code to perform crashworthiness and occupant safety simulations in the automotive industry and other transportation industries. The LS-DYNA family of codes also includes: **LS-DYNA Implicit, LS-PRE** and **LS-POST**, and **LS-OPT**. In crashworthiness simulations, two models (*Neon*, and *3-car-crash* models) have become *de facto* explicit dynamics benchmarks, and are routinely used to assess the scalability and performance of clusters sold by hardware vendors. See the "topcrunch" site (developed under DARPA support) by Professor David Benson et al at UC San Diego. [The "topcrunch" site also offers a parallel implicit benchmark problem offered by Dr. Yong-Cheng Liu of ANSYS, Inc.]. Engineering Technology Associates (ETA), a LS-DYNA distributor in Madison Heights, MI, also has developed its own **eta/DYNAFORM** metal forming code and the **eta/VPG** (Virtual Proving Ground) vehicle dynamics and NVH code – each with its own customized application-specific interface, but using LS-DYNA as the core solver. [www.lstc.com], [www.topcrunch.org], and [www.eta.com]

ESI/PAM-CRASH – PAM-CRASH was developed in the l980s by Dr. Eberhard Haug et al, starting from the public-domain LLNL DYNA3D explicit transient code as its basis. The developer is ESI Group (Rungis, France). ESI has developed a family of other related FEA/CAE codes, such as: *Virtual Prototyping:* **PAM-CRASH 2G**; *Virtual Manufacturing:* **PAM-STAMP 2G, PAM-TUBE 2G,** and **PAM-FORM**; *Virtual Environment:* **PAM-FLOW** and **PAM-CEM**. [www.esi-group.com]

TNO/MADYMO – The occupant safety code MADYMO used worldwide is developed and supported by TNO (Delft, The Netherlands) – which has recently formed a separate business entity named *TASS* (TNO Automotive Safety Solutions) to sell and support MADYMO. MADYMO is used for simulating the behavior of airbags, seat belts, dummies, fenders, etc. TNO also possesses an unparalleled database of crash and occupant safety test data. It has interfaces to the two leading crashworthiness codes in the world: LSTC/LS-DYNA and ESI/PAM-CRASH 2G. [www.madymo.com]

Altair/HYPERMESH – HYPERMESH, a user-friendly FEA pre- and postprocessor, is developed and supported by Altair Engineering in Troy MI. It came onto the market after SUPERTAB and PATRAN, and has gained sizable market share, especially in the auto companies. [www.altair.com]

Exa/PowerFLOW – Exa/PowerFLOW is a "digital physics" flow code that has attracted a number of CFD customers worldwide, especially in the automotive industry (e.g., BMW). Exa Corporation (Lexington, MA) was founded in 1991 by MIT Professor Kim Molvig. [www.exa.com]

ICEM CFD – This versatile CFD pre- and postprocessor, developed by ICEM CFD Engineering, was founded by Dr. Armin Wulf. It interfaces with all the leading CAD codes and CFD codes, plus some FEA codes, and is used in many industries worldwide. The company was acquired by ANSYS, Inc. in 2001, and the code is now known as **ANSYS ICEM CFD**. [www.ansys.com]

ANSOFT – The ANSOFT FEA code has three families of products: high frequency; electromagnetics; and signal integrity. These can be use to study, for instance: RF and microwave components, printed circuit boards, IC packaging, high-performance interconnects, electromechanical systems (e.g., electric motors, drives, actuators, sensors), circuit designs, and antennas. Ansoft Corporation (Pittsburgh, PA) was founded by Dr. Zoltan J. Cendes (Chairman and CTO), and Dr. Nick Csendes is the CEO. Its recent financial performance has been stellar in the past year, and its stock has been in the low $30's. [www.ansoft.com]

The leading injection molding FEA code in the plastics industry is the **MOLDFLOW** code, developed by Moldflow Pty Ltd., which was founded by Colin Austin in Australia in 1982. Currently, A. Roland Thomas is the Chairman, President, and CEO of Moldflow Corporation. MOLDFLOW has interfaces with ABAQUS and ANSYS. [www.moldflow.com]

In the Design Optimization, Probabilistic Design, and DOE (Design of Experiments) area, some leading codes are, for example: Vanderplaats R&D's **Genesis** [www.vrand.com]; Engineous Software's (Dr. Siu Tong et al) **iSIGHT** and **FIPER** codes [www.engineous.com]; Dr. Nielen Stander's LSTC/**LS-OPT** [www.lstc.com]; and Red Cedar Technology's (Drs. Ron Averill and Erik Goodman) **HEED** code [www.redcedartech.com]. For more information, the reader is referred to the URL's listed for each code.

2.4 PDA/MVISION materials data base

One large and well-known materials data base that is very useful for FEA is **MSC.Mvision**. PDA/MVISION was first developed at PDA Engineering by Dr. Edward L. Stanton (also co-developer of PDA/PATRAN), partnered with Battelle Memorial Institute, and other testing organizations and laboratories. When MSC.Software acquired PDA Engineering, MVISION was renamed MSC.Mvision. It provides temperature- and time-dependent material properties data for many commonly used metals and non-metallics, in tabular form or plotted, and is especially comprehensive for composite materials. [www.mscsoftware.com]

No discussion of the past developments of FEA/MCAE codes would be complete without the mention of concomitant developments in CAD (MCAD) codes, and rapid computer hardware advances in the 1970s and 1980s.

2.5 Early CAD Codes

The two CAD industry pioneers are generally acknowledged to be: Dr. Ivan E. Sutherland (who, at 69, is still doing outstanding computing research at Sun Labs) – whose seminal 1963 MIT Ph.D thesis *Sketchpad* spawned the development of the entire interactive computer graphics field; and Dr. Patrick C. Hanratty – whom many call "the father of CAD/CAM." Hanratty first wrote the "Pronto" numerical control program in 1957, and founded MCS, Inc. (Scottsdale, AZ) in 1971 – to develop the **ANVIL**-series of CAD/CAM codes [www.mcsaz.com]. The history of CAD/CAM historical development is briefly highlighted here; the interested reader is referred to the excellent site [www.cadazz.com/cad-software-history], which provides a detailed narrative history by successive time segments, from which the following summary timeline is taken.

1960s	Computervision/CADDS McDonnell Douglas/CADD (1966) => later McAUTO/Unigraphics Applicon Intergraph Auto-trol/AD380 CDC/CD-2000 Gerber Scientific/IDS-3 GE Calma MCS/ANVIL GM Research Labs/DAC (Design Automate by Computer) Ford/PDGS (1967) Lockheed/CADAM (1967)

1970s	*Most CAD systems were still 2D, then 3D CAD arrived.* MIT researchers (e.g., S.A. Coons, 1967 – "Coons patch") French CAD researchers:Citroen (deCasteljian); Renault (Bezier) NIST started IGES (1979), graphics exchange standard format.

1980-85	*Mainframes gave way to minicomputers and Unix workstations.* DEC VAX 11/780 popular in the CAD/CAM/CAE marketplace. Intergraph went public (1981). Dassault's new subsidiary Dassault Systemes developed CATIA v.1 (1981), and signed reseller agreement with IBM (which lasts to today – 26 years later). CAD industry revenue exceeded $1 billion (1981). IBM introduced 1st PC (8/12/1981) – The IBM 5150 had an Intel 8088 chip (4.77 MHz), 16-640 KiB memory. Designed by a team headed by Don Estridge, Boca Raton, Florida. (It was discontinued on 4/2/1987.) Auto-trol introduced 1st CAD software for PCs (1982). Bentley Systems and Intergraph did the same (1984). PDES succeeded IGES (1984), as graphics data exchange format. Dassault Systemes released CATIA v.2 (1985). CAD/CAE work was dominated by Sun, SGI, Apollo, DEC VAX.

1986-89	*Complacency by CAD vendors . . . things went Parametric!* Parametric Technology Corporation kicked butt in the CAD marketplace; releasing new code enhancements every six months! Dassault acquired CADAM from Lockheed (1986). PTC released Pro/Engineer on first Unix workstation, got a sizable market share within first 18 months. All CAD vendors got a wake-up call by PTC; respond or perish. Boeing decided in 1988 to use DS/CATIA to design its 777. ($1B+ revenue for IBM-Dassault!) UG acquired Shape Data from Evans & Sutherland (1986). Spatial Technology established to develop ACIS solid model

kernel (1986) – adopted by HP's ME CAD system (1989).
Solid model kernel battle among: ACIS, Parasolid, and Ricoh's Designbase.
SGI 3D workstations became very popular, for CAD/MCAE work.
1990 rank of CAD vendors: (1) DS/CATIA; (2) PTC Pro/E; (3) McDonnell Douglas/Unigraphics; (4) SDRC I-DEAS

1990-94 Windows NT PCs introduced, and began to take market share from Unix workstations.
Boeing succeeded with "all CATIA - no paper" design strategy on 777 (1990), reduced physical mockups, and saved much time and money.
Pratt & Whitney and GE Aircraft Engines standardized on UG.
Mercedes Benz, Chrysler, Renault, and Honda standardized on CATIA.
Caterpillar standardized on PTC Pro/E.
GM adopted UG; EDS acquired UG (1991).
Computervision/CADDS and Intergraph/I-EMS faltered badly.
IBM lost $5B (1992).
1993 CAD market share: IBM-DS/CATIA; EDS-UG; PTC; SDRC.
Autodesk/AutoCAD rode PC wave to big success in 2D CAD, with 1992 revenue of $285M (vs. UGS's $130M).
Autodesk sold its 1-millionth AutoCAD license (1994), rel. 1.3 featured 3D CAD, solid model based on ACIS.
Microsoft released first 32-bit OS for PCs running Windows NT.
Intel released its first 32-bit Pentium Pro processor.
SolidWorks made its debut – Windows NT-based (1993).

1995-97 *SolidWorks dominated – on rise of Windows NT platform.*
Explosive rise in PDM systems (e.g., Sherpa)
UG developed Information Manager, later became iMAN.
SDRC and CDC partnered to develop Metaphase (1991-2).
Adra System developed MatrixOne.
SolidWorks 95 was now 3D CAD – "80% of Pro/E's functionality at 20% of the price" was its marketing slogan.
Aggressive marketing of 3D CAD software in sub-$10K range.
Windows NT (and Intel) could now handle serious 3D CAD tasks (circa 1997).
Dassault Systemes acquired SolidWorks for $320M (1997).
EDS-UG acquired Intergraph/SolidEdge.
Autodesk released "Mechanical Desktop", first full-function 3D solid modeling CAD software.

2.6 **Hardware Advances** (through early 1980s)

Leading **mainframe and supercomputer** vendors in the 1970s and 1980s were, for example: IBM, CDC, Univac, Burroughs, Honeywell, GE, Cray Research, Fujitsu, NEC, Hitachi, and Siemens. The leading **minicomputer** vendors were DEC VAX 11/780 (1977), Prime Computer, Data General, and Harris. In engineering **workstations**, the early pacesetter was

Apollo Computers (with its proprietary DOMAIN networking system); Digital tried, in vain, to counter with its MicroVAX workstation. Sun Microsystems (1982) – featuring its own Solaris Unix OS (developed by co-founder Bill Joy) and open standards – swept the workstation market by the mid- to late 1980s. IBM developed its first PC in 1981. Apple Macintosh made its debut in 1984 – announcing it in that memorable Super Bowl TV ad (shown only once). In the mid-1980s to early 1990s, Silicon Graphics, Inc. (founded by Dr. Jim H. Clark et al in 1982) created a 3D graphics workstation niche, and became very popular with CAD and MCAE users.

Some key hardware developments during this period are summarized in the following timeline.

Computer developments timeline:

1946 ENIAC I designed and installed at University of Pennsylvania,
(Cost $500,000.) Invented by John Mauchly and J.P. Eckert.
1947 Transistor invented by William Shockley et al (Nobel Prize in Physics, 1956).
1953 IBM's first general-purpose computer – the IBM 650 installed at Columbia University.
1954 FORTRAN language born – first high-level programming language – invented by IBM team led by John Backus; IBM (Hollerith) keypunch cards used as input.
1961 First commercial integrated circuit developed at Fairchild Semiconductor Corporation – invented by Robert Noyce and Jack Kilby (Nobel Prize in Physics, 2000).
1963 Mouse invented and patented by Douglas Engelbart, Stanford Research Institute, Menlo Park, CA.
1964 CDC introduced CDC6600 with 60-bit words, and grabbed a large part of the scientific, engineering, and HPC markets. BASIC language created. First graphics tablet introduced.
1977 DEC introduced VAX11/780 minicomputer, followed soon by Prime, Data General, Harris, etc.
1980s Apollo workstation, DEC MicroVAX, Sun Microsystems, etc. battled in "workstation wars."
1982 - Early 1990s SGI introduced first 3D workstation, and dominated the 3D CAD market and also became popular in MCAE markets. SGI standardized the 3D API environment with SGI Irix GL, which later became the OpenGL standard.

2.7 FEA / MCAE Conferences

Attending a conference is an excellent way to present one's research, ideas and applications to other engineers, to listen to FEA/MCAE software developers' latest developments – and to network with one's peers and exchange experiences. The following paragraphs describe some well-known FEA/MCAE conferences that were held in the mid-1960s to 1970s-1980s:

Wright-Patterson Air Force Base FEM Conferences – This series of three FEM conferences – 1st (1965), 2nd (1968), and 3rd (1971) – on "Matrix Methods in Structural Mechanics" were held by the Air Force Institute of Technology in Dayton, Ohio. The conference organizer was AFIT Dean Dr. J. S. Przemienicki, the author of a popular early book on matrix methods of structural analysis. Many well-known FEM researchers from around the world attended these three conferences, and presented important papers on their latest findings.

World Congress on Finite Elements – This series of "commercial" FEM/FEA conferences (as opposed to "academic" FEM research), held every four years, was organized by Dr. John Robinson, who during this period also published the popular and newsy *Finite Element News* magazine. Robinson was also an early supporter of NAFEMS – the Glasgow-based international agency that continues today to promote FEA standards, benchmarking, training, documentation, and user certification.

Chautauqua's – The Chautauqua conferences on recent developments in FEA, MCAE, and CAD/CAM was organized by Dr. Harry G. Schaeffer, a CAE consultant and FEM professor known for his book, *MSC/NASTRAN Primer.*

AIAA/ASME/ASCE/AHS Structures, Structural Dynamics, and Materials Conferences – These "SDM" conferences were held every two years. At the 23rd SDM conference (1982) in New Orleans, I presented a paper comparing and evaluating eight general-purpose FEA programs (Fong, 1982). My paper was received well by the audience, and caused intense interest among FEA users worldwide (as well as a bit of controversy among commercial FEA code developers). This wide user interest led to our organizing a *Finite Element Standards Forum,* held at the 24th SDM (1984) in Palm Springs, co-chaired by Lockheed's Dr. Kevin J. Forsberg and myself (Forsberg and Fong, 1984). Approximately 150 people attended this forum and provided their feedback. They included: most of the leading FEA code developers, prominent academic FEM researchers, and many FEA users. At this *Forum*, Dr. Richard MacNeal and Robert Harder of MSC proposed a set of linear FEA standard benchmark problems (to test convergence, accuracy, and validity) to the FEM/FEA community. These problems were subsequently known as the *MacNeal-Harder benchmarks*, and were published in Professor Walter Pilkey's FEM/FEA journal entitled *Finite Elements in Analysis and Design*.

NAFEMS Conferences – The NAFEMS Conferences, held every four years, bring together FEA/MCAE practitioners, researchers, software and hardware vendors to exchange ideas and discuss the latest FEA/MCAE and CAD/CAM developments. The next NAFEMS conference will be held in Vancouver, BC, Canada, in May 2007. Please see the NAFEMS website for additional information. [www.nafems.com]

2.8 My FEA anecdote

My most embarrassing FEA experience happened in 1984, when I was a FEA project manager at PDA Engineering. My colleague Donna and I applied the ROSAAS composites FEA code (developed by Dr. J. Greg Crose, a PDA Engineering co-founder) to predict the critical stresses in a composite rocket nozzle. The customer was Aeroject-General Corporation, a leading rocket manufacturer. After a month's FEA work, we attended a "critical design review" meeting at Aerojet's facilities in Sacramento, California. Donna presented our FEM model of the rocket nozzle, material properties used, applied loads, boundary conditions, and our predicted FEA results at the critical throat region of the nozzle.

Sitting way in the back of the room, there was a white-haired, older gentleman, who had kept quiet up to that moment. He raised his hand, and politely questioned the validity of our FEA results – claiming that the critical stresses in the throat area should be *tensile*, rather than compressive as we had shown. Based on the design's composite materials layup and the expected flight loads and temperatures, he said his experience and instincts told him that we should expect tensile stresses in the critical throat area. That was a hush of silence in the room, and many people nodded in agreement. Donna and I were terribly embarrassed, when we realized that we had indeed input the loads using the wrong sign. The man was absolutely correct, of course. Turns out – I found out a month later – that this astute gentleman was Dr. Paul Longfellow, Aerojet's corporate "guru" (with 30+ years of composites design experience) – who was invited to attend *every* Aerojet critical design review. Donna and I never forgot that painful FEA lesson – garbage in, garbage out! The story reminds us that a FEA analyst should *always* check the results, to make sure they make sense.

Part 3. Maturing of MCAE Markets (1990s to Today)

With Blackberrys and iPODs everywhere, will we soon see FEA on a Blackberry or iPOD nano?

This statement is not as far-fetched as one might think. An affordable laptop or notebook computer these days can already perform FEA of a moderately- sized finite element model. Who knows what is possible 25 years from now? Perhaps, one day someone will invent a way to store all the rule-based MCAE experts' advice on a Dick Tracy watch . . . or a FEA engineer will be able to mesh a finite element model on a gadget the size of Lieutenant Commander Data's communication device pinned on his left chest? Forty years ago, would anyone have foreseen the powerful computing devices and Internet we have today?

An article (by reporter Keay Davidson) from the 3/3/07 *San Francisco Chronicle* newspaper caught my attention the other day. It described the immense computer power at LLNL, that helped the Lawrence Livermore National Laboratory (LLNL) win a recent "Reliable Replacement Warheads" design competition over its sister lab in New Mexico, Los Alamos National Laboratory (LANL). LANL had developed the first atomic bomb (the *Manhattan Project*) in July 1945, made possible by a brilliant scientific team headed by Dr. J. Robert Oppenheimer. Nowadays. LLNL's *360-teraflop* (and designed to attain *petaflops*) IBM Blue Gene/L supercomputer is *10 million times faster* than computers circa 1992 (only 15 years ago), right after the Cold War ended. LLNL scientists can perform a 3D computer simulation of a nuclear weapon blast, "from beginning to end". (This suggests a real atomic warhead does not have to be tested at the Nevada Test Site any more, like in the 1970s.) Such a *mega*-computer simulation will run about 6 weeks, versus computers that would have taken 60,000 years to do this simulation in the early 1990s.

3.1 M&A in CAD / MCAE

In Part 2, I have already mentioned how the larger CAD/MCAE companies have acquired the smaller ones, for instance: (1) **MSC.Software's** acquisition of Aries, PDA, MARC, CSAR, and UAI; (2) **ANSYS Inc.'s** acquisition of ICEM CFD, CFX, and Fluent, Inc. (which had previously bought Fluid Dynamics International); (3) **LMS International's** acquisition of the CADSI/DADS kinematics code (it competes against MSC.Adams); (4) **UGS's** acquisition of Shape Data, Intergraph/Solid Edge, and SDRC (which had previously bought Enterprise Software/FEMAP), and then started selling NX Nastran in June 2004; (5) **PTC's** acquisition of Rasna Corporation – and renaming it Pro/MECHANICA; (6) **Dassault Systemes'** acquisition of CADAM, Spatial Technology, SolidWorks, SRAC/COSMOS, and ABAQUS, Inc. (making ABAQUS part of its new SIMULIA analysis suite)

It's rather difficult for a CAD/MCAE user to keep track of all these mergers and acquisitions. All the customer really cares about is whether the software product quality and technical support remain the same, improve, or get worse – and whether one has to pay more for the different CAD/MCAE codes needed for design and FEA.

The next time you go to a Chinese restaurant, your fortune cookie will probably say: “One thing is for sure; change in CAD/MCAE is inevitable.”

3.2 2nd Generation CAD-MCAE Interfaces

An example of the second generation of MCAE pre- and postprocessors is ANSYS’s **Workbench**. If you haven’t seen this slick modern CAD/MCAE interface, ask your ANSYS salesperson (or distributor) to give you a quick demo. Virtually every functionality and widget you want are now there. This interface is intuitive and well laid out. The user can render the incoming CAD geometry or the meshed FEA model. The GUI will easily spawn your FEA model to a linear/nonlinear FEA or CFD simulation – prompting you to input all the necessary parameters to fully describe your FEA, e.g.: model completeness, material properties, loads (mechanical, thermal, gravity, dynamic, etc.), and boundary conditions. This interface makes the engineer’s finite element modeling task, FEA, and the results evaluation task easy, efficient, and enjoyable.

Other CAD/MCAE software vendors offer their own FEA pre- and postprocessing software, “suites,” or interfaces/translators, for instance: **Altair/HYPERWORKS 7.0**, **MSC.Sofy**, **EASi**, **FEMAP**, **DS/SIMULIA**, **CEI/EnSight**, **Intelligent Light/FIELDVIEW**, etc. EASi (Madison Heights, MI), originally a MCAE software developer, has for many years now specialized in outsourcing design, CAD, and MCAE projects to its larger office in Bangalore, India. It also has partnered with ESI Group, to co-develop interfaces or stand-alone, verticalized CAE modules – which are then marketed and supported by ESI: EASi-CRASH DYNA; EASi-CRASH RAD; EASi-CRASH MAD; EASi-FOLDER; EASi-SEAL; EASi PROCESS, and EASi BASIC NASTRAN.

3.3 HP Now #1 in Tech

I just read the 3/12/07 issue of *Forbes* magazine. The cover article highlights how Hewlett Packard has just overtaken IBM to become the new *#1 in Tech,* with 2006 year-end sales of $92 billion (IBM has held the #1 spot for four decades).

After HP’s board dismissed CEO Carly Fiorina in February 2005, the board hired Mark Hurd (formerly, CEO of NCR) to be the new HP Chairman and CEO. When Fiorina was at the helm for 5.5 years, HP’s stock fell 56%, the company lost money, morale was bad, and HP was hurting. HP’s 2001 takeover of Compaq for $19 billion (which Fiorina instigated) was very controversial, and resulted in much dissent on the board, led by co-founder William Hewlett’s son, Walter. (It remains to be seen whether Fiorina was right in advocating this acquisition, after all, and whether this bold move has made HP stronger. Some industry analysts suggest that HP’s recent successes have vindicated Fiorina’s move.)

Mark Hurd – an operational whiz with an eye for details, numbers, and accountability – went to work, quietly. He laid off 15,300 people – but with no loss of revenues. In the 23 months since Hurd has come onboard, HP’s stock price has doubled, and its net income has risen 158%, to $6 billion for the fiscal year that ended 10/31/06. In its printer business (which always has been the company’s cash cow – with annual revenue of $27 billion and accounting for 29% of the company’s total revenue), HP had a 45% market share in 2006 Q3. Every day, HP sells 8,200 big servers worldwide, and ten times that many PCs. And, in October 2006, HP eclipsed Dell as the world’s #1 seller of PCs!

3.4 IBM’s Turnaround under Lou Gerstner

When Lou Gerstner came in as CEO of IBM in April 1993, IBM was bleeding, and in danger of going out of business. Gerstner achieved a miracle in 9.5 years, and turned the Big Blue "elephant" around and "taught it how to dance" – Gerstner later wrote a best-selling book with this title. (He resigned in December 2002, to become the Chairman of The Carlyle Group, a well-networked private equity investment group of very wealthy individuals.) He changed IBM's culture. There were many industry skeptics who believed that Gertsner would not be able to turn IBM around, because he had a "no tech" background (CEO of RJR Nabisco, and senior positions at American Express and McKinsey & Co.). In a December 2002 talk he gave to Harvard Business School MBA students, Gerstner quipped that in his first all-day, strategy meeting with IBM executives, they all talked in a peculiar techno-babble that only IBM'ers could understand. He didn't understand anything that was said, and wondered whether he had indeed taken on the wrong job.

Gerstner proceeded to remake the company, and grow the IBM Global Services division to be the biggest consulting business in the world – with 190,000 consultants worldwide, offering industry solutions and expertise in various vertical markets, and accounting for 50%+ of IBM's revenue. Gerstner taught IBM'ers to focus on the customer, and to thoroughly understand each client's organizational behavior. (I have a good friend who has worked for IBM Global Services for 10 years. He told me that in the first 2 to 3 meetings with a new client, he and his team members each bring a clipboard – and all they do is *listen*.)

Of course, Gerstner didn't do it all by himself; he had the capable help of some very talented IBM executives. One such talent, for example, is Dr. Irving Wladawsky-Berger, IBM's VP of Technical Strategy and Innovation and well known in HPC circles, who is retiring this June after an illustrious, 37-year career. Among the important IBM business initiatives and projects he has headed in he past 12 years: Internet strategy in the mid-1990s; Linux strategy (IBM already offered AIX and Windows OS's – so why bring in the penguin?); Grid Computing; Autonomic Computing; and since October 2002, the "On Demand" Business Initiative. All multibillion influences and impacts on IBM's core business.

3.5 The Fast Rise of the Penguin and Its Impact on HPC

In the HPC markets, the customers (especially in academia) are very tough – but many have switched to Linux (whose universal logo is the penguin). They all want great price/performance, but are "cheap" and only willing to pay the lowest possible price. That's why you sometimes hear computer sales people complain that these HPC Linux server sales are becoming zero-margin "commodity" sales – so why are they even doing it?

When Finnish undergrad Linus Torvalds first developed the Linux kernel for his 1996 M.S. thesis, he put it on the Internet in the mid-1990s and made it *open-source*, It was a brilliant move whose time had come. Many people initially ridiculed this OS, where bugs are fixed by software developers in the public domain. Linux was also considered to be difficult to manage, easy to hack, and requiring specialized development tools. If every hardware vendor offers Linux, how can one differentiate from the competition? But wait a minute, the open-source OS comes with an unbeatable price – it is free! How do you compete against something that's free?

Torvalds came to Silicon Valley after graduating from college, and worked at specialty chipmaker Transmeta Corporation from 1997 to 2003. Meanwhile, in the late 1990s, at least three Linux vendors – Red Hat, VA Linux Systems, SuSE – started offering Linux as a product and charged customers for technical support. In gratitude for Torvald's creation, Red Hat and

VA Linux gave Torvalds stock options. When they both went public in 1999, Torvalds had a net worth of over $20 million. He is now at Linux Foundation (Beaverton, OR), a software consortium. For his creation of Linux, he has been honored by many organizations. In 1996, the Asteroid 9793 was named "Torvalds" in his honor. And, in April 2004, *Time* magazine named Torvalds the "free software champion" and one of the most influential people in the world.

3.6 Microsoft Now Offers 64-bit HPC Clustering Software

Microsoft at first pooh-poohed the penguin, considered Linux not robust enough to be a serious business threat, and continued to push Windows – even in HPC markets. This attitude changed when within a few years, Linux surprised everyone and captured 10-15 percent share of HPC markets (e.g., manufacturing/MCAE; oil and gas, alternative fuels; genomics [understanding the human genome and the genomes of other species] and proteomics [protein structure folding]; Wall Street risk management; government national labs, etc.).

Many MCAE customers (including one major auto maker I've visited often) still will not trust their mission-critical business applications (Oracle, SAP, etc.) to Linux, because of security reasons. They continue to use a version of Unix for IT and in their new server procurements. All the major hardware vendors, however, started in the late 1990s to offer Linux as an alternate OS to their customers: IBM, HP, Dell, Fujitsu, etc. And finally, Sun jumped on the Linux bandwagon in late 2005 (when it began offering Opteron-based servers, designed by Andy Bechtolsheim's team, that run Solaris, Linux, or Windows OS's).

Microsoft, which had been honing its HPC clustering software and tools for several years, finally modified its HPC strategy in the past year and now offers a Linux option. In June 2006, Microsoft launched its 64-bit *Windows Compute Cluster Server 2003* (CCS) clustering software for HPC applications. In the press release, it quoted the support of 33 partners, including eight leading MCAE software vendors (ABAQUS, ANSYS, CD adapco, ESI Group, Fluent, Inc., Livermore Software Technology Corporation, Mecalog, and MSC.Software) who committed their software to be ported to CCS by the end of 2006. MS-MPI is offered as the message passing interface, which is compatible with MPICH2. CCS supports a variety of interconnects: gigabit Ethernet; remote direct memory access (RDMA); Infiniband; and Myrinet. CCS also supports third-party compilers. One leading MCAE software vendor (ANSYS) has been carefully evaluating this CCS clustering software in 2006, and one of their HPC staff members told me recently that their preliminary benchmarking results using CCS have been quite good.

3.7 Clustering, Scalability, and MPI

It is well known that in MCAE applications, most of the explicit crash codes and CFD codes are parallelized and scale fairly well (meaning almost linearly), while the implicit FEA structural analysis codes do not. The current *sweet spot* for implicit FEA code usage worldwide averages 4 compute nodes (and 8 in a few HPC installations). For explicit crash codes and CFD codes, the current sweet spot in a cluster is 16 nodes (going up to 32). A "sweet spot" means that a MCAE code scales satisfactorily up to that node count, but becomes inefficient beyond that node count (i.e., there is negligible improvement in simulation speed even with an increasing number of processors).

Therefore, based on my own observations in visits to many MCAE customers worldwide in various industries, most of the recent HPC/MCAE cluster purchases are for **4 processors** in servers (or, two dual-node engineering workstations working in tandem) intended **for implicit FEA codes** (e.g., ANSYS, MSC.Nastran, ABAQUS, LS-DYNA Implicit, etc.). The sweet spot is currently **16 processors** in server clusters intended **for crashworthiness and occupant safety simulations** (e.g., LS-DYNA, PAM-CRASH, etc.) or **CFD simulations** (e.g., ANSYS/FLUENT, STAR-CD, ANSYS/CFX, etc.). Beyond these "sweet spot" node counts, a cluster is not cost-effective because of the poor scalability in the FEA codes.

In a **typical MCAE procurement** to decide what size cluster to buy, the HPC customer usually insists on seeing benchmark results for his/her MCAE codes (using standard benchmarks for these codes, or typical FEA models used in his/her environment), and then, good price/performance. Once a hardware vendor has gotten past the benchmarking phase and has demonstrated adequate performance and scalability on a number of relevant MCAE codes, the final decision then goes to the Purchasing Department. This department is tasked with getting the best deal (meaning the lowest price). Once in a while, one may see a sales situation where an engineering manager favors a certain computer vendor, or the incumbent vendor, for some reason (e.g., because of trust gained in the past for excellent technical support), and tries to "stack the deck" in writing the proposal's requirements to favor that vendor. This is rare, however, especially after the Sarbanes-Oxley Act was passed in 2002 to ensure sound financial practice and corporate governance.

The increasingly higher prices for software licensing managers (e.g., Macrovision/FLEXlm, etc.) and for Linux OS's (e.g., Red Hat, etc.) have recently become serious issues in some purchase requisitions. Many MCAE software vendors (e.g., LSTC) opt to write their own secure licensing software for floating licenses. And, some customers prefer to use open-source Linux as their OS, rather than purchasing one from the commercial Linux vendors.

The **Message Passing Interface (MPI)** protocol has become standard in HPC environments. Each hardware vendor has developed its own implementation of MPI (for example, "HP-MPI") and claims it has the best performance. At Ohio State University (Columbus, OH), Professor D. K. Panda and his colleagues have developed **MVAPICH2** (a high-performance MPI over Infiniband) open-source software, which is in its final development stage and is already being used by more than 455 organizations in 30 countries. [see www.cse.ohio-state.edu/~panda for more information.]

3.7 Interconnects

More than half of the fastest 500 computer systems in the world [see www.top500.org, which updates this Top 500 list twice a year] still use the relatively inexpensive gigabit Ethernet switch for clustering. Other popular moderate- and high-performance interconnects include, for example:

- Myricom/**Myrinet** [www.myricom.com]
- **Quadrics** [www.quadrics.com]
- **Scali** [www.scali.com]
- **Infiniband** interconnects:
  - Cisco/**Topspin** [www.cisco.com]
  - **Voltaire** [www.voltaire.com]
  - QLogic/**Silverstorm** [www.qlogic.com], [www.silverstorm.com]
    (Note: QLogic acquired Silverstorm Technologies for $60 million in October 2006, after its February 2006 $109-million acquisition of **Pathscale, Inc**., another vendor of Infiniband SAN fabric interconnects and also a developer of compilers.)
  - **Mellanox** [www.mellanox.com]

(Note: Mellanox Technologies had a successful IPO on 2/13/07. Its 2006 revenue was $49.5 million, an increase of 15% over that of 2005.)

3.8 "Intel and AMD Hate Each Other"

In the 3/19/07 issue of *Fortune* magazine, an article by David Kirkpatrick used these exact words in the subtitle of his article on the current battle between Intel and AMD. The full title: "The Joy of Blood Feuds – Intel and AMD hate each other. **And that's great for customers.**"

For the first time, Advanced Micro Devices (AMD) had developed a competitive Opteron processor in 2003, which gave it a clear performance lead over Intel. This performance advantage enabled AMD to convince major computer makers to use its processor in their servers and workstations: IBM, HP, then Sun in 2005. Finally, in 2006, the last holdout, Dell, announced it would abandon its Intel-only policy and use Opteron chips in its servers. From a negligible market share in servers in 2003, AMD quickly used its performance lead to capture about 22 percent market share by the end of 2006. This is huge, because servers are where the most profits are made in the processor business.

The AMD Opteron processor features an innovative, multiple point-to-point HyperTransport technology, which interconnects coupled AMD Opteron processors to large pools of low-latency memory. This eliminates front-side-bus bottlenecks, and accelerates the most challenging compute- and memory-intensive applications. The AMD Opteron chip also uses less power than comparable Intel (and Itanium) chips, thus generating less heat in server clusters in the data center. This ***power and cooling*** issue has become *the* biggest concern for customers and an important decision factor, whether a data center is used for business or HPC applications. AMD therefore has favored a measure of *performance per watt of electricity used,* for this very reason. Intel had historically used raw speed as its favorite measure.

Intel had to respond. It cut costs, announced major layoffs, and went all out to improve the performance of its newer single-core, dual-core, and quad-core processor designs. In mid-2006, Intel unveiled its latest dual-core *Woodcrest* chip, that mostly exceeded or tied AMD Opteron's benchmark numbers for the leading CAD, FEA (e.g., MSC.Nastran), CFD, and crash codes (e.g., LS-DYNA). Then, in late 2006, Intel beat AMD and shipped the first quad-core processor named *Clovertown*. So, recently, for the first time in the past several years, Intel has started to recapture server market share, and it also dropped prices. Even though this hurt Intel's margins, it seriously wounded AMD – so AMD's stock price dropped, while Intel's went up.

The competition is continuing – furiously. In early fall of this year, AMD is expected to ship its new quad-core processor, code-named *Barcelona.* This quad-core chip is expected to beat Clovertown's performance by 40 percent, according to AMD. Intel is expected to respond, and then AMD will respond again, and so forth. This nip-and-tuck competition is expected to go on for some time – which is great for customers. For the first time, it's a level playing field.

To make good business sense, major hardware vendors (like IBM, HP, Sun, and Dell) will have no choice but to offer servers that feature both Intel and AMD processors.

In July 2006, AMD acquired the graphics chip manufacturer, ATI Technologies (Markham, Ontario – [www.ati.amd.com]), for a whopping $5.4 billion. This move was seen by some industry observers as AMD's thrust into the huge game industry. ATI competes with Nvidia, the leading graphics chip manufacturer [www.nvidia.com]. A Nvidia Quadro graphics accelerator is used, for example, inside a Sun Java Ultra 20 Workstation or Java Ultra 40 Workstation.

3.9 Current Server Market Revenues (2006 Q4)

In the 2/27/07 issue of the *San Francisco Chronicle*, reporter Tom Abate wrote an article which summarized the **2006 Q4 worldwide server revenue growth** for the top three server vendors (according to IDC estimates), showing that Sun had jumped past Dell and climbed from 4th to 3rd place – and grew much faster than IBM and HP in that quarter:

Vendor	*Revenue ($ billions) in 2006 Q4*	*Growth (%)*
1. IBM	5.8	+3.8
2. HP	4.1	+5.1
3. Sun	1.5	+24.4*

* Gartner's estimate for Sun's server revenue growth in Q4 of 2006 was +17%.

This is indeed great news for Sun Microsystems, which has struggled the past six years and the company's viability was even questionable just two years ago. This growth demonstrates the market success and competitiveness of Sun's new line of AMD Opteron-based servers, which came out in 2005 and offers customers a choice of Solaris, Linux, or Windows OS. These Sun servers were designed by a team headed by Andy Bechtolsheim, a company co-founder (and a renowned thermal-mechanical packaging expert as well as a successful serial entrepreneur) who returned to Sun in February 2005 to spearhead the development of Sun's new AMD Opteron-based servers.

In 2006, Sun had displaced Dell Computers from the No. 3 spot in server sales. For Dell, in the quarter that ended 2/2/07, it earned $673 million (or 30 cents per share), as compared to $1.01 billion (43 cents per year) a year earlier. Its revenue fell 4%, to $14.4 billion. (Note that these figures are for all of Dell's products, not for its servers.)

3.10 MCAE Today and Tomorrow's Challenges

So, what do all the above trends and changes in business landscape, hardware, software, OS, and tools mean for MCAE – now and in the future? Here are some issues and challenges:

Infrastructure – Because of its deep pockets, worldwide reach, and marketing muscle, Microsoft's new 64-bit clustering software will no doubt make an impact on HPC and other markets. The question is how much? Bill Gates has recently taken on a lesser role as Chairman (to devote more time and energy to The Bill and Melinda Gates Foundation), and he and CEO Steve Balmer brought in Ray Ozzie, developer of *Lotus Notes*, to be the Chief Technical Officer. Ozzie and his management team, no doubt, are taking a serious look at Internet-based strategies (Google's success being a wakeup call), and they will try to figure out how to compete effectively against the likes of Yahoo, Google, etc.

The major hardware vendors (HP, IBM, Sun, Dell) will likely continue to sell both Intel- and AMD Opteron-based servers and workstations, offering the customer a choice of two processors and three OS's: Unix, Linux, and Windows. Good technical support (including 24x7 “platinum” support) will help each to differentiate. Power and cooling will continue to be the big issue in data centers, and “total cost of ownership” is often more important than the initial procurement cost. All the usual CAD/MCAE issues will likely still remain: ease of use; interface with CAD; training; technical support; on-line documentation; and price/performance.

The CAD/MCAE software vendors, in order to stay competitive, will always strive to improve computational efficiency, and lower the customer’s cost. M&A activities and the shakeout in CAD/MCAE will likely continue; the big fish will eat the small fish.

Grid Computing – Some customers, in order to maximize the use of existing hardware, have implemented Grid Computing in their environments.

With increasingly complex designs and globally dispersed operations, manufacturers need effective tools to enable them to collaborate with multiple teams and partners, and get the most from their computational resources. Grid Computing helps by letting disparate systems to be pooled and managed as a common computing resource. Yes, this sounds like the data centers from the 1970s being reborn again (e.g., Control Data’s *Cybernet, Boeing Computing Services, United Computing Services*) In the 1976-1981 period, I ran batch FEA jobs (punched cards input format) using ANSYS and ABAQUS, at a Cybernet office in Los Angeles. Typically, such jobs were turned around overnight.

About five years ago, Ford Motor Company (Dearborn, MI) hired Raytheon Co., a missiles and electronics manufacturer but acting as a system integrator in this case, to use *Sun Grid Engine* middleware to connect together 500 workstations. These workstations were used by Ford engineers to do MCAD work (SDRC I-DEAS) during the day, but sat idle at night. Raytheon and Sun helped Ford connect these workstations together into a grid using Sun Grid Engine. At night, SGE would manage the FEA jobs (ABAQUS, MSC.Nastran), according to job priority and estimated run time. This Grid Computing implementation was so successful and efficient that Ford management retained Raytheon to do the same grid implementation at their Dunton UK and Cologne/Merkenich (Germany) facilities, working with a European partner named Cards Engineering. Ford has a worldwide network, and design and FEA engineers in different locations can access and interactively look at each other’s models and analysis results.

The three leading Grid Computing middleware vendors are:

- **Platform Computing/LSF 7.0** and **LSF HPC**, in Markham, Ontario, Canada [www.platform.com]
- **Sun Microsystems/Sun Grid Engine 6** [www.sun.com/software/gridware], [http://gridengine.sunsource.net] Santa Clara, CA. (The SGE development team is based in Regensburg, Germany.)
- **Altair Engineering/PBS Pro 8.0** [www.altair.com]. Troy, MI

The interested reader is encouraged to contact each vendor for an overview of its products, history, customer base, sample applications, and pricing.

In my opinion, Grid Computing still has a way to go before reaching “critical mass” and gain widespread acceptance in industry. Many managers understand the benefits of Grid Computing. The technical aspects are usually straightforward and solvable. Yet, implementation is sometimes problematic due to a variety of factors – not the least of which are an organization’s culture and internal inter-departmental politics.

Mentoring – Many of the older FEM pioneers, professors, researchers, and FEA engineers have retired or passed on. Who is going to take their place, and mentor and teach the younger engineers and new graduates just beginning their careers? The answer to this dilemma is complex. Some companies try to cope with this transition problem by interviewing their in-house experts in various technical disciplines, and then building a rule-based expert system. Drs. Pedro Marcal and Robert Melosh had developed such a *SAGE* expert system in the late 1970s, using the MARC code and architecture as a framework, for a biomechanics FEA application and working with researchers from Stanford Medical School.

FEA challenges – FEM has become the dominant numerical analysis method since the early 1970s. However, many FEA analytical difficulties (and pricing issues) still remain, for example:

- lack of adequate failure theories (for metals; and non-metallics such as composites, plastics, polymers, rubber, concrete, glass, wood, resins, foams, seat belt fabrics, etc.)
- material properties vs. temperature and vs. time
- modeling of biological materials (bone, soft tissues, cartilage, skin, hair, and other viscoelastic materials) needed for biomechanics and biomedical applications. For instance: *What is the Poisson's ratio for 'live' human skin?* Gillette and Braun, the American and German razor and shaver manufacturers, have used MARC and ABAQUS *to model the human skin-hair interface when someone is shaving.* How does the FEA analyst account for a man who has very thick whiskers, versus someone who has thin ones and not much facial hair? *How does one simulate the intravenous pumping rate of the delivery of a proper amount of medication into a patient's diseased heart?* Too slow, the patient will not get enough medication; too fast, the patient will die.
- fatigue data of metals, nonmetallics, and composite materials
- friction and viscosity laws, e.g., between dissimilar materials. *How does one properly model the hydroplaning (skidding) of a car tire when the pavement is wet? How about when there's a patch of oil?*
- thermal data (e.g., absorptivity, emissivity needed for radiation calculations; material properties of solder in electronics modules and printed circuit boards)
- cracks and imperfections in components and materials – known imperfections in shells (e.g., tin or aluminum cans for soft drinks and beer) after fabrication
- nonlinear FEA benchmark problems – no consensus yet in industry
- quality assurance – of a myriad of combinations of element types, materials, boundary conditions, loads, and environments.
- software licensing management and pricing issues
- how does a MCAE/FEA software developer properly charge for the software when chip manufacturers produce dual-core, quad-core (and perhaps in the future, 8-core and 16-core) processor designs? Are two dual-core processors the same price as a 4-node processor? Are four quad-core processors in a system the same price as a 16-node cluster? (The definition of a "cpu" has changed.)
- time lag – an estimated 7 to 10 years before promising academic research results are actually implemented in commercial FEA codes.

Emergence of China and India as formidable competitors – Everybody says these two Asian countries are the two to watch in this new century. We are all aware of China's emergence as a major manufacturing power; the U.S. has a huge trade deficit with China. India is known primarily for its software engineering expertise, and its prowess in outsourcing. Many large Indian companies are becoming quite well-known internationally, e.g.,: Wipro; Infosys; Tata Consultancy Services (TCS), etc. These two countries produce hundreds of thousands of mathematicians, engineers, and scientists a year, probably 10 times the number of U.S.'s math, engineering, and science graduates. Because of China's and India's improving economies, many foreign-born but U.S. trained expatriates have returned to China and India to pursue better opportunities, or are seriously contemplating to do so (*a reverse brain drain*). This hurts our pool of available engineers, scientific researchers, and software engineers – and U.S.'s future competitiveness.

I personally know about fifteen foreign-born and U.S.-educated Chinese American professionals who have returned to work in China in the past five years, typically to Shanghai and Beijing. One such example is an experienced woman FEA engineer who worked many years in Detroit and recently returned to Shanghai (where she came from originally) with her entire family. She is experienced in performing crashworthiness and occupant safety simulations using LSTC/LS-DYNA and TNO/MADYMO.

Last year, I visited TCS in Bangalore, India, and was very impressed by the caliber of the five TCS engineers I met and the quality of their engineering work. Each possessed a Ph.D degree (typically in mechanical engineering), specializes in one or more FEA codes (ABAQUS, ANSYS, MSC.Nastran, FLUENT, and LS-DYNA), and is a lead FEA analyst or group manager. They asked very intelligent, perceptive questions.

Reliance of U.S. hi-tech industries on foreign-born but U.S.-trained graduate engineers – Our government's H-1B visa policy is always controversial, for political, economic, and social reasons. The U.S. is not graduating nearly enough engineers and scientists to satisfy our hi-tech industry needs. But, some politicians want to keep foreign-born engineers and scientists out, and keep such jobs at home. Others (like Bill Gates) lament that Microsoft cannot hire nearly enough skilled workers ("short 3,000 a year"), and advocate that "our need for H-1B visas is infinite." Sadly, for the American economy, our universities are not graduating enough people in math, science, engineering, and computer science. This education gap hurts U.S. competitiveness. Fixing this situation should be a national priority.

The world's most innovative and successful companies now all use CAD/MCAE to gain the competitive edge – and stay ahead. The March 19, 2007 issue of *Fortune* magazine lists "The World's 10 Most Admired Companies." The top five: (1) General Electric (which has led the pack in 7 of the last 9 years); (2) Toyota Motor; (3) Procter & Gamble; (4) Johnson & Johnson; and (5) Apple. All these five leaders (plus #9 BMW) use CAD/MCAE tools routinely to design and develop their current and future products. You can bet that if computers improve the next 15 years like they have the past 15 (say 10 million times faster), these leading companies will still be using improved CAD/MCAE tools to design their future products. There will be undoubtedly changes in: workflow (FEA jobs will turn around in 2 minutes, instead of the current overnight turnaround, for reasonably large jobs); operations; manufacturing processes; human resource practices; and employee training.

[Thank you for reading this article. Please feel free to contact me at: henryhfong@yahoo.com if you have any comments. The opinions and personal comments in this 3-part article are my own, and do not reflect the endorsement or opinion of *FEA Information* nor its staff.]

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GLOSSARY

CAE computer-aided engineering (usually refers to a design/analysis process that includes preprocessing, FEA, postprocessing – with the analysis step typically involving the specification of material properties, boundary conditions, and loads)

CFD computational fluid dynamics (e.g. CFD codes such as: ANSYS/FLUENT, STAR-CD, ANSYS/CFX, Acusim, Exa/PowerFLOW, etc.)

Computational mechanics a term favored by academic FEM researchers, with an emphasis on the numerical analysis, convergence, and accuracy aspects of solid and fluid mechanics

EDA electronic design automation, also known as ECAD (leading vendors being Cadence, Synopsys, and Mentor Graphics)

FEA finite element analysis

FEM finite element method; finite element model

HPC high performance computing, also used: HPTC (high performance technical computing). Typical HPC markets include, for example: MCAE, life sciences (genomics), oil and gas, risk management, etc.

IGES Initial Graphics Exchange Specification (sponsored in 1979 by the National Institute of Science and Technology [NIST])

MCAD mechanical computer-aided design, also used: **CAD**. The term refers to software (e.g., CATIA, UGS, PTC, SolidWorks, AutoCAD, etc.) that is used to generate a geometric representation of an object. [The term MCAD usually does *not* include analysis capabilities.]

MCAE mechanical computer-aided engineering – a term which includes pre- and postprocessing and FEA (but not MCAD geometry)

MDO multidisciplinary optimization (e.g., VR&D/Genesis and VisualDOC, Engineous Software/iSIGHT and FIPER, LSTC/LS-OPT, HEEDS, etc.)

NAFEMS National Agency for Finite Element Methods and Standards, a Scotland-based (but international in coverage) agency that publishes FEM and FEA-related documentation, standards, benchmark problems, and training/certification. See www.nafems.org for a description of the agency, their publications, and steering committees in various FEA technical disciplines.

NVH noise, vibration, and harshness – used in the automotive industry as a measure of ride comfort in a vehicle.
PDES Product Data Exchange Specification (sponsored by NIST, succeeded IGES in 1984)
PDM product data management
PLM product lifecycle management (e.g., DS/Enovia, UGS/Metaphase, etc.)

American professional societies in engineering:
AHS American Helicopter Society
AIAA American Institute of Aeronautics and Astronautics
ASCE American Society of Civil Engineers
ASME American Society of Mechanical Engineers
USACM United States Association for Computational Mechanics

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