Working together online:
The challenge and promise of collaborative Internet computing

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Outline

1. The field of collaborative Internet computing
   - What is collaborative Internet computing?
   - The challenge of achieving interactivity in Internet environments
   - The challenge of maintaining consistency in collaborative Internet computing environments

2. The REDUCE project: approach and experience
   - REDUCE approach to interactivity and consistency
   - REDUCE techniques and achievements
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3. Conclusions
What is Internet computing?

- **Internet Computing (IC)** is the area that studies the technologies of the Internet and Internet-based computing systems and applications.

- Internet is at the core of information revolution which changes the way we:
  - **communicate**: email, e-conferencing, Internet telephony
  - **do business**: electronic commerce
  - **learn**: distance learning, digital library
  - **work**: Internet-supported collaborative work
  - **play**: video-on-demand, network-based multi-player games

- A major **trend** in Internet computing is to use the Internet to enhance human-to-human interaction and communication.
What is collaborative computing?

- **Collaborative Computing (CC)** is the area that studies how to support human-to-human interaction and collaboration using computing technology.

- Collaborative computing represents a shift in emphasis from using computers to support the work of an individual user to using computers to support interaction and collaboration of a user group. In other words, CC is about how to use computers to support people working together.

- A major trend in collaborative computing is to develop Internet-based applications to support collaboration among geographically dispersed people. Representative systems:
  - Email
  - Collaborative editors
  - Multi-player games
What is collaborative Internet computing?

- **Collaborative Internet Computing (CIC)** is the area that studies the technologies and applications at the intersection of collaborative and Internet computing. In other words, CIC is about how to support people working together online.

- Three characteristic components of a CIC system:
  1. Multiple collaborating users
  2. Human-computer interaction interfaces
  3. The Internet
For many applications, bandwidth is what counts

- **Telemedicine**: To retrieve a series of medical test images for a patient at a moment’s notice in the event of emergency, up to 40 gigabits (40,000,000,000 bits) may need to be transferred from an off-site storage to a hospital over the Internet.

- **Virtual meeting, or videoconferencing**:  
  - Meeting without travel: each meeting room contains a spherical camera and one or more people. The bit streams from each of the cameras are combined to give the illusion that everyone is in the same room. Bandwidth requirement is stupendous.  
  - It can be used for remote school, getting medical opinions from distant specialists, and numerous other applications.

- **Video-on-demand**: To select any movie or TV program ever made, in any country, and have it displayed on your screen instantly.

With each increase in network bandwidth, new applications become possible.
For many others, latency is what matters

- A range of collaborative Internet applications do not need to send very much data or to send a continuous stream of packets, but the little bits they occasionally send should be delivered and responded quickly. E.g.,
  - Collaborative editors,
  - Networked games,
  - Distributed Virtual Environments.
Their typical packet size is less than 40 bytes.

- To create a quality interactive experience to human users, the system response delay should be less than $100 \text{ ms}$ (100 milliseconds = 0.1 second).

- However, the Internet communication latency is much longer than this interactivity requirement.
The challenge of achieving interactivity in Internet environments

“The entire focus of the industry is on bandwidth, but the true killer is latency.”

--- Prof M. Satyanarayanna (CMU), keynote address to ACM Mobicom’96.
Domestic communication latency in AARNet (Australian Academic and Research Network)

- Performance objective: 98% of all domestic Off-Net packets will have a National Round Trip Time (NRTT) of less than or equal to 300 ms.

- The typical round trip delays between the PoP at Brisbane and other PoPs:
  - Sydney (18 ms);
  - Canberra (26 ms);
  - Melbourne (36 ms);
  - S. Australia (48 ms);
  - Hobart (53 ms);
  - W. Australia (83 ms);
The international performance objective is for 95% of all International packets to have an International Round Trip Time (IRTT) of less than 650ms between Sydney and the USA West Coast.

Typically the performance is around 300ms.
International bandwidth and latency in AARNet

- The current 310 Mbps (310,000,000 bits per second) is expected to increase to 1.2 Gbps (1,200,000,000 bits per second) by August 2002.
- Gigabit networks give better bandwidth but not necessarily shorter latency. E.g. Sending 310 Kb (310,000 bits) from Sydney to Seattle:
  - Latency over a 310 Mbps network: 1ms + 300ms = 301ms
  - Latency over a 1.2 Gbps network: 0.25ms + 300ms = 300.25ms
Home users without direct Internet connection have to dial into an ISP using a modem.

A typical home-ISP modem round-trip latency is 150ms.

If two users are connected via ISPs, the total round-trip latency caused by modems is $150 \times 2 = 300$ ms.
Bandwidth still matters

- Bandwidth is important not only for its own sake, but also for its effect on overall communication latency.

- Latency caused by Home-ISP connection is not negligible. A private 64 Kbps network connection has the same average bandwidth as a small share (1/150) of a larger bandwidth (10 Mbps) network connection, but has a very different latency effect:
  - Transmitting 40kb over 64kb connection always takes 10 seconds.
  - Transmitting 40kb over 10Mb connection takes 32 ms at the best, or 64 ms on the average.

  If you have a choice, take the small share of a larger bandwidth.

- Latency caused by congestion (queuing delay and retransmission delay) in the Internet backbone is still significant.
100 ms is the threshold value of user noticeable response delay in many interactive applications.

The latency for an inter-continental interaction is well-above this threshold:

- Home-ISP *modem delay*: $150\text{ms} \times 2 = 300 \text{ ms}$
- Internet *round-trip propagation delay*: $300 \text{ ms}$.
- Delay due to network *congestion, retransmission, and indirect routing*: non-deterministic (120 seconds is the worst case life time of an Internet packet).
- Delay due to host *computer speed limitation and timesharing OS software*: non-deterministic.
- A *total delay* observable from Internet-based applications: several minutes.
The need for latency-hiding techniques

- As the networking hardware technology improves, latency can be reduced, but there is an ultimate limit:  
  - The speed of light in glass fiber: \( 200 \text{km/ms} \).
  - Circumference of earth: \( 40,000 \text{ km} \).
  - Total round-trip delay: \( \frac{40,000}{200,000} = 200 \text{ms} \).

- For a range of collaborative Internet applications, the key to achieving quality interactivity is to use latency-hiding techniques, that help create the illusion that the latency is lower than it really is.

- Example latency-hiding techniques:
  - Data replication/caching
  - Mobile code (e.g., Java applets, software agents)
  - Asynchronous communication protocols
  - State prediction techniques (e.g., dead-reckoning in Distributed Virtual Environments)
  - Optimistic concurrency control techniques (e.g., operational transformation in collaborative editors)
Achieving responsiveness by replication

- **Replication** is a widely used latency-hiding technique
  - Collaboration is mediated by a shared virtual environment.
  - The shared environment is replicated at all collaborating user sites.
  - A local user’s operation is responded to quickly, according to its effect on the local replica, and then asynchronously propagated to remote replicas to keep them consistent.

- Computing responses locally is not new – even the human body does it. If we touch a hot object, we react by quickly withdrawing the limb in question. That quick response is controlled by local nerves not the brain, because sending the pain signal all the way to the brain and waiting for a response would take too long.

- However, replication causes **consistency problems**.
Consistency maintenance is a fundamental and challenging issue in many areas of computing, such as computer architecture, operating systems, and database systems. CIC systems are quite different from these traditional computing systems because of the involvement of interactive human users and the Internet environment. Consequently, consistency maintenance for CIC systems requires significant new research.
Human users are part of the CIC communication hierarchy

- **Application**
- **Presentation**
- **Session**
- **Transport**
- **Network**
- **Data link**
- **Physical**

**Network**

**Application** protocol

**Presentation** protocol

**Session** protocol

**Transport** protocol

**Network** protocol

**Data link** protocol

**Physical** protocol

**Human protocol**
Why CIC consistency maintenance is special?

- The factor of interactive human users:
  Involvement of human users in CIC systems calls for consistency requirements that are different from what (e.g., serialisability) used in traditional database and distributed computing systems.

  - Human users possess the ability to tolerate and resolve some inconsistency problems, which may be taken advantage of to relax some consistency requirements on the underlying system.

  - Human users have special needs for responsiveness and unconstrained interaction and collaboration, which may impose non-traditional consistency requirements on the underlying system.
The factor of Internet latency:

- Consistency maintenance techniques in traditional database and distributed applications are often based on **synchronous** communication protocols and **pessimistic** concurrency control (which prevents inconsistency from occurring), which work well in low-latency Local Area Network environments but do not scale to high-latency Wide Area Network environments, such as the Internet.

- **Asynchronous** communication protocols plus **optimistic** concurrency control (which allows inconsistencies to occur and provides mechanisms for human users to resolve them) are more efficient in the Internet environment and more suitable to human users involved in the CIC systems.
Addressing the challenge of collaborative Internet computing

The REDUCE project: approach and experience (1994 – Present)
Overview of the REDUCE project

REDUCE stands for REal-time Distributed Unconstrained Collaborative Environment (Partially Funded by Australian Research Council)

Objectives:
1. To investigate the underlying principles and techniques for supporting human-to-human interaction and collaboration over the Internet.

2. To design and implement collaborative Internet computing systems for evaluating and demonstrating the research results.

Research vehicle:
Real-time CE (Collaborative Editing) systems.
What is a real-time CE system?

- Real-time CE systems allow multiple geographically dispersed users to view and edit a shared document at the same time over the Internet.

- In CE systems, collaboration is mediated by shared documents; and interaction is modeled by user initiated editing operations.

- Shared documents can be:
  - Text document
  - Graphics document
  - Hypermedia document
  - Multi-player games state
  - Multi-user virtual reality state.
Why target editors?

- They are useful.

- They serve excellent vehicles for exploring a range of fundamental and challenging issues, including:
  - Consistency maintenance,
  - Concurrent control,
  - Collaborative undo,
  - Collaborative notification, and
  - Collaborative human-computer interface techniques.

- They can model a wide range of CIC applications:
  - Collaborative CAD (Computer Aided Design),
  - Collaborative CASE (Computer Aided Software Engineering),
  - Multi-player games
One significant challenge

Consistency maintenance under the following constraints:

- **High responsiveness:**
  - response time to local operations should be short (< 100ms)

- **High concurrency:**
  - Concurrently editing any objects at any time

- **High communication latency:**
  - non-negligible and non-deterministic
Document replication

REDUCE has adopted replication as the strategy of achieving high responsiveness in the Internet environment.

- Each shared document is replicated at all collaborating sites.
- A local operation is executed on the local replica immediately to achieve high responsiveness.
- A local operation is also propagated to remote sites to achieve consistency of multiple replicas.

How to maintain a consistent replicated document in the face of concurrent editing operations?
The challenge of defining suitable criteria for consistency

- Ideally, all replicas should be kept *strictly consistency*, i.e., all replicas are identical all the times.

- However, it is *impossible* to achieve strict consistency because the *communication latency* between collaborating sites is non-negligible.

- Also, it is *unnecessary* to insist strict consistency because temporary divergence among replicas may be tolerable by *human users*. 
The REDUCE approach to consistency maintenance

Convergence

Replicas may be divergent after executing different operations (to achieve high responsiveness and high concurrency).

Replicas must be convergent after executing the same group of operations (to achieve consistency).

Convergence means to ensure that all users have the same document at the end of a session.
Intention preservation

The intention of an operation $O$ is the effect that can be achieved by executing $O$ on the document state from which $O$ was generated.

The intention of $O_2$ is to delete 2 characters at position 3 ("CD")

$O_2$’s intention is preserved when it is executed on the local replica "ABCDE".

Intention preservation: The intention of any operation must be preserved at all sites.

Intention preservation means to ensure that the local operation effect observed by a user is the same as its remote effect observed by other users in the face of concurrency.
Causality-preservation

Causality preservation means to ensure that users’ actions are always performed in their natural cause-effect order during a session.

This user may be confused by seeing the answer before the question!

This is the correct execution order
The REDUCE consistency model

A CE system is consistent if it maintains the following properties:

- **Convergence**: When all sites have executed the same set of operations, all replicas of the shared document are identical.
- **Intention preservation**: The effect of executing an operation $O$ on any remote document state is the same as executing $O$ on the local document state.
- **Causality preservation**: If $O_a$ is causally before $O_b$, then $O_a$ is executed before $O_b$ at all sites.

Implications of the CIC properties:

- No ordering constraint is imposed on independent operations → high responsiveness and high concurrency
- **Identical results** are ensured even if independent operations are executed in different orders.
- The identical result is not achievable by any serialization protocol.

This consistency model has been widely accepted as a theoretical framework for systematically addressing consistency problems in this area.
The need for technological innovation

None of the existing distributed computing and database technologies is able to preserve the CIC properties:

- **Turn-taking:**
  - Unable to support concurrent editing.

- **Locking:**
  - Unable to preserve CIC properties.

- **Serialization:**
  - Unable to achieve intention preservation.

- **Causal ordering:**
  - Unable to achieve convergence or intention preservation.

- **Transaction:**
  - ACID properties do not match CIC properties.
Operational Transformation

A technical innovation from collaborative computing research


Basic idea of Operational Transformation (OT)

- Given two concurrent operations $O_1$ and $O_2$. If $O_1' = T(O_1, O_2)$, and $O_2' = T(O_2, O_1)$, where $T$ is a transformation function, then, $[O_1 \circ O_2] \equiv [O_2 \circ O_1']$.

$O_1 = \text{Ins}[1, "X"]$ 
$O_2 = \text{Ins}[3, "Y"]$

Local operations are executed as-is.

Remote concurrent operations are transformed before execution.

OT is able to maintain consistency (convergence and intention preservation) without imposing any restriction on users' activities, i.e., users can edit any object at any time.
A well-known OT Puzzle: the challenge of ensuring OT correctness

The search for a solution to this and other OT puzzles has been a major stimulus to the development of OT technology.
Evolution of the OT technique

**GROVE:** by a team led by Ellis at MCC (Microelectronics and Computer Technology Corporation).


This was the pioneer work on OT and often-cited, but its core algorithm (dOPT) was flawed (the later well-known dOPT puzzle).

**REDUCE:** by a team led by Sun at Griffith University.

- We discovered the dOPT puzzle in **1994**, and spent over one year to devise a solution to this puzzle in **1995**. The solution is based on the use of a *linear* history buffer.
- Our initial result was not recognized and accepted by a major ACM conference or journal until **1997** (ACM GROUP’97) and **1998** (ACM Transaction on Computer Human Interaction (TOCHI)).
- Since then, our follow-up results have enjoyed six (6) consecutive years acceptance in highly competitive ACM GROUP and CSCW conferences (which accept less than 20% submissions), and 3 major papers accepted by the prestigious ACM TOCHI (which publishes 8 - 12 papers per year).
Other independent solutions on the dOPT puzzle

- **CCU (Calculus for Concurrent Update):** by Cormack, University of Waterloo, Canada. A counterexample to the dOPT algorithm was given and a theory CCU was proposed to help resolve the puzzle (no solution). This result was documented in an internal technical report in 1995.

- **Jupiter:** by Nichols et al, Xerox PARC (Palo Alto Research Center), USA. The Jupiter collaboration system used a new OT control algorithm based on the use of a 2-dimensional state space, which is able to partially resolve the dOPT puzzle. Published in ACM User Interface Software and Technology conference, 1995.

- **adOPTed:** by Ressel et al, University of Stuttgart, Germany. This solution was based on the use of a $N$-dimensional interaction graph. Published at ACM CSCW’96 (According to Ressel, more than 2 years were spent in search of this solution).
International collaboration on OT

- C. Sun and C.A. Ellis met at ACM GROUP'97, and decided to write a paper to review the evolution of operational transformation techniques, with the goals of identifying the major issues, achievements, and remaining challenges, and promoting international collaboration in this area. This paper was well-received at ACM Conf. on CSCW, 1998 and later often-cited.

  Ellis, as an international collaborator in REDUCE, joined Sun in a successful ARC large grant application in 1999.

- A Special Interest Group on Collaborative Editing (SIGCE) was set up in 1998 (during ACM CSCW'98), which consists of active researchers from Australia, United States, Canada, Germany, France, Netherlands, Hong Kong, China, Korea, Japan, etc. The REDUCE team plays a leading role in SIGCE.

- International Workshop on Collaborative Editing Systems organized by SIGCE in conjunction with:
  - ACM GROUP, Nov. 14, 1999, Phoenix, USA
  - ACM CSCW, Dec. 2, 2000, Philadelphia, USA
  - ACM GROUP, Sept. 30, 2001, Colorado, USA.
  - ACM CSCW, Nov. 17, 2002, New Orleans, USA.
Supporting collaborative undo

- The ability to undo operations (for error-recovery, alternative exploration, and try-and-failure learning) is a standard feature of modern interactive applications.
- It is very challenging to support undo in collaborative applications because of the interleaving of operations by multiple users.
- None of the existing collaborative undo solutions is able to provide the capability of undoing any operation at any time.
- Using OT as the core technique, REDUCE is the first to provide such a capability for group editors.

Supporting locking in Internet environments

- Locking is a standard technique in distributed computing and database systems used to ensure data integrity by prohibiting concurrent conflicting updates on shared data objects.
- The OT technique has been extended to support optional, fine-grain, and responsive locking in Internet-based collaborative systems.
- This novel locking technique can be applied to a range of Internet-based applications for achieving semantic consistency.


Supporting collaborative design of web documents

- A recent major advancement of the OT technique is the extension from the linear text domain to the domain of tree-like hierarchically structured documents, such as SGML, XML, or HTML.

- It is this extension that leverages the OT technique to support collaborative design of web documents.

Further extension and application of OT (4)

Supporting notification for both real-time and non-real-time collaboration

- Notification is an essential feature of collaborative applications and plays a major role in determining the application’s capability in supporting real-time and/or non-real-time collaboration.
- A recent major advancement of the OT technique is the extension to support notification in both real-time and non-real-time collaborative applications (one example of non-real-time collaboration is the CVS version control system).

H.F. Shen and C. Sun:
"Flexible Notification for Collaborative Systems,"
Addressing the challenge of building working systems

From theory to prototype

1. To investigate system design and implementation issues.

2. To demonstrate the feasibility of the state-of-the-art collaborative editing technologies.

3. To facilitate usability studies of collaborative editors.
An Internet-based REDUCE demo system

The first publicly accessible collaborative editor

Demonstrated at
- ACM conference on CSCW, Dec. 2000
- www.acm.org/siggroup/demos.html
- www.computer.org/dsonline/collaborative/systems.html
Dear Dr Sun,

I saw your ACM paper, "Consistency Maintenance and Group Undo in Real-Time Group Editors" on the web, and thought you might be able to give me a pointer. I'm chairing a team that will be spending a month cooperatively developing a software spec. I'm the lead author but am soliciting input from the rest of the team, which is scattered around the country.

So I'm looking for a tool that will help the team (20 people) collaboratively develop a document. Ideally it will allow me to publish a Word or HTML document on the web, and allow the other members of the team to view it and annotate it. I'd like them to be able to attach comments sort of like sticky-notes to locations in the document, that could then be viewed and printed by other team members. If you know of anything that's publicly available, free or cheap, and pretty robust, I'd love to hear about it.

Thanks in advance,

Jeff Pepper
President and CEO, ElderVision
215 Allegheny Avenue, Oakmont PA 15139 USA
Dear Jeff,
Your proposed collaborative documentation scenario is very interesting and can be an excellent application for collaborative editing technologies and tools. Unfortunately, to my knowledge, there has been no free or commercial collaborative editing tool directly suitable for supporting your application.

Our REDUCE demo (available at http://reduce.qpsf.edu.au) is still a research prototype, though efforts are directed toward making it more useful, flexible and robust (we are also developing an Internet-based collaborative XML editor using REDUCE technology).

I suggest you have a look at the following IEEE web site: http://www.computer.org/dsonline/collaborative/collaborativeproducts.htm to see whether there is anything close to your need.

Chengzheng
Dear Chengzheng,

Thank you for helping me try out the REDUCE demo yesterday, but I could not get it to work for me properly ...

I think REDUCE is a great project but far too complex for our needs. I should mention that the people collaborating in our project are non-technical people, mostly administrators in nursing homes. They could probably handle a simple web based application, where they enter a url, receive a page of html text, and can use some simple commands to add and view annotations to the page. Anything more complex, such as REDUCE's interface, would almost certainly blow them out of the water.

I'll keep looking for something like this, but it sounds unlikely. **Maybe you and your team could build it... :)**

Best regards,

Jeff
Addressing the challenge of building useful applications:

From prototype to product

For collaborative editors to gain user acceptance, they must be compatible with popular single-user editors in functionality and interface features, as well as be able to support multi-user editing,

Basic Strategy:
Integrating REDUCE technology into existing single-user editors
Ongoing work in converting single-user editors into collaborative editors

1. **Collaboration aware approach**: modifying the source code of the target single-user editor: *Amaya XML editor*

2. **Collaboration transparent approach**: without modifying the source code of the target single-user editor: *Microsoft Word*.
REDUCE-spawned Projects

The REDUCE project has spawned a number of new research projects and evolved into a comprehensive and coherent research program.

- **GRACE**: GRAphics Collaborative Editing
- **RECIPE**: REal-time Collaborative Interactive Programming Environment
- **FORCE**: Flexible Operation-based Revision Control Environment
- **NICE**: Notification-flexIble Collaborative Editing
- **INVEST**: INternet-based Visualization Environment for Science and Technology
- **IMAGINE**: Internet-based Multi-plAyer GamINg Environment
- **COACT**: COllaborAtive Commerce environment
Through the GRACE project, we have successfully applied the REDUCE consistency model to the graphics domain.

Major results:

- Consistency maintenance and conflict resolution techniques
  - Multi-version objects technology
  - Collaborative undo of multi-version objects.
  - Optional locking on multi-version objects
- A real-time collaborative object-based graphic editor prototype

Applying the GRACE technology to Genetic Software Engineering

MICROWAVE OVEN - 4th Integration Step

1. USER ?Button-Pushed? [Pushed]
2. BUTTON [Pushed]
3. OVEN [Cooking]
4. USER ?Door-Closed? [Energized]
5. DOOR [Closed]
6. LIGHT [Off]
7. USER ?Door-Opened? [Open]
8. OVEN [Idle]
9. LIGHT [Off]
11. BUTTON [Pushed]
12. POWER-TUBE [Energized]
13. OVEN [Cooking]
14. USER ?Door-Closed? [Energized]
15. OVEN [Cooking]
16. USER ?Door-Opened? [Open]
17. OVEN [Idle]
18. LIGHT [Off]
19. USER ?Door-Closed? [Energized]
20. OVEN [Cooking]
21. USER ?Timed-Out?? [Energized]
22. LIGHT [Off]
23. USER ?Door-Closed? [Energized]
24. POWER-TUBE [Off]
25. USER [Cooking-Finished]
26. BEEPER [Sounded]
27. USER [Cooking-Finished]
Collaborative programming is an emerging software engineering methodology, which aims to improve both productivity and quality of programming by using multiple programmers to work on the same design, code, algorithm, or test. (J. Nosek: “The case for collaborative programming” CACM 41:3, March 1998, pp.105-108)

Through the RECIPE project, we are applying the REDUCE technology to support collaborative programming over the Internet in real-time.
The emerging area of networked gaming

- Networked computer games are one of the few Internet applications for which end users are actually willing to pay money. Games like Ultima Online, Doom, Quake, and others have attracted several million players worldwide.
- As the Internet becomes ubiquitous through wireless and cheaper Internet access, the audience for networked computer games will increase rapidly, creating a mass market with a multi-billion dollar volume.
- However, most Internet-based computer games have encountered a large number of inherent technical challenges, ranging from inadequate support by network and transport protocols to consistency maintenance problems and security breaches (or cheating as players prefer to call it).
- At the same time scientists have begun to discover networked computer games as an extremely challenging and rewarding area of research. What makes this area of research particularly fascinating to us is that many problems in networked games are very similar to what we found in CE, and many solutions found in CE research can be adopted to networked games, and vice versa.
IMAGINE: Internet-based Multi-Player Gaming Environment

Research focus: achieving interactivity and consistency in Internet-based multi-player gaming environment, in which the shared objects can change their states not only in reaction to user operations, but also to the passage of time.
Other emerging areas

- **Mobile collaborative computing:**
  - Real-time collaboration using mobile computers. Specific issues: multi-device collaboration and dynamic replication and migration of shared applications.
  - Non-real-time mobile access to shared data. Specific issues: automatic hoarding and merging of replicated mobile data.

- **Ad hoc communications and collaboration in ubiquitous computing environments.**
  - Such environments are characterized by a profusion of computational devices that are connected to each other and the Internet at large by heterogeneous networks.
  - Such environments enable new forms of spontaneous and informal interactions among individuals who are organized in an unforeseeable way.

- **More to emerge ...**
The REDUCE experience

The following factors have contributed to our success in establishing and maintaining international competitiveness in the area of collaborative Internet computing:

1. Choose the right target.

2. Stay focused and persistent.

3. Keep the research program coherent and open.

4. Publish at major conferences (first) and journals (second).

5. Have a supportive and rewarding environment.
Conclusions

- Collaborative Internet computing is an extremely challenging, competitive, and rewarding area of research.

- Through the REDUCE program, we have established our international reputation in this area.

- To maintain our momentum and international competitiveness in this rapidly expanding area, it is essential that we are equipped with the necessary resources, including advanced computing and networking infrastructure, adequate funding for RHD scholarships and research assistance, and sufficient time to do research.
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- Family members.

I could not have done this without you!