and refinement, measurement refocusing, visualization and knowledge generation can be addressed comprehensively within the rubric of DDDAS.

In the following, some specific examples are presented to motivate and convey the kinds of requirements, challenges and capabilities developed within the scope of the funded DDDAS projects.

"the project illustrates the kind of synergistic research and technology advances that are needed for accurate and timely predictions of…. the actual events that occurred …"

A project (*General DDDAS Framework with Coast and Environment Modeling Applications*) funded under the recent DDDAS solicitation, deals with environmental situations such as those that occurred with the recent Katrina hurricane and it's effects therein. The scope of this project illustrates many of the challenges that arise when applying and enabling DDDAS capabilities. Additionally, the project illustrates the kind of synergistic research and technology advances that are needed for accurate and timely predictions of the course of the hurricane, the water surge, the resulting toppling of the levies. In some ways, the actual events that occurred as a consequence of Katrina had been speculated. However, because of the inaccuracies of the traditional modeling approaches, the power of definite and concrete predictions was lacking, with an ensuing strategy of "wait and see" that was adopted, with respect to the evacuation of the population, followed by "ad-hoc" emergency response afterwards, with the disastrous consequences that ensued. Traditional methods that employ models driven only by static input data in isolation, are completely inadequate for providing realistic, real-time forecasts, essential for complex phenomena analysis, and, in this specific example, for decision making and response to the subsequent actual emergency.

"… powerful new methods for more accurate analysis and decision support systems, which can be deployed to accurately predict the onset of such critical events and guide decision making …"

This example and other critical events such as tornadic events, coastal oil spills, contaminant transport in the atmosphere, are application areas that are studied in projects investigated/pursued under the DDDAS rubric. The dynamic modeling capability enabled with the DDDAS concept, is able to provide powerful new methods for more accurate analysis and decision support systems, which can be deployed to accurately predict the onset of such critical events and guide decision making in taking appropriate mitigation actions. In the funded project, which is dealing with events such as Katrina, the hurricane is continually monitored by: radar, satellites, aircraft, as well as other sensors, all of which provide rich and continuous streams of data. This project develops capabilities so that such data are dynamically fed into sophisticated simulation codes (that have been developed to model and forecast the intensity, wind speed, etc.) in order to more accurately predict the projected paths of the storms themselves, their interaction with the oceans underneath, the developing storm surge that ensues, the waves that develop, the interaction of surge and waves with the wetlands and rivers, stresses on levees and other structural analysis aspects, and floods that may develop. Each simulation code uses the dynamically input data to resolve unique and specific features at very different scales, involving different physical processes, and so on. In the DDDAS funded project application-modeling methods and systems software are developed to enable combining these data streams and simulation codes in a comprehensive and dynamic way, thereby enabling to adaptively refine forecasts, invoke appropriate algorithms needed if the hurricane is projected to pass over different types of terrain, or to request, additional data, to refine the simulations or to incorporate in the simulation new or modified data streams as the storm is forecasted to move over different locations.

"…project encompasses synergistic research in all areas critical to DDDAS: applications, systems, software, measurement, and algorithms …"

Such a project encompasses synergistic research in all areas critical to DDDAS: applications, systems, software, measurement, and algorithms. For example algorithms are developed to distill voluminous data streams into appropriate dynamic inputs to the simulation codes, ability to dynamically invoke the appropriate simulation models, request and discover appropriate computational and other resources on which can accommodate the varying computational requirements based on the streamed data, or to execute appropriate ensembles of models. Other capabilities needed are ability to preempt nonessential jobs executing on critical resources; assemble the results from the various models and compare it with on-going and up-to-date observations. Based on this information, the best performing models can be updated with new conditions, and the cycle is repeated, in a dynamic control loop between the on-line acquired (or archival) measurements and the executing simulations. Simultaneously, output from storm tracking models can be fed into storm surge models, which in turn can be fed into wave models, and subsequently to local levee and flooding models. Each of these models execute on different time and length scales, contain different physical aspects of the system, and involve different mathematical algorithms and error properties. Based on the analysis and predictions from the ensemble of models, sensors and other instruments can be steered to acquire more accurate and relevant real-time data that are streamed back to appropriate applications to further improve the accuracy of the predictions. Such information, provided by a fully developed DDDAS process, can then be fed directly to emergency response agencies, providing a valuable tool for determining where and how to respond, which areas to evacuate, which highways to open or close, or where to place supplies or station red cross workers.

As shown in the list of the supported projects, the scope includes a wealth of many other projects dealing with physical systems, and additional examples are elaborated-on in the other subsection.

"Eventually the suite of the technologies developed under these projects can be put together to enable end-to-end, prediction, impact, response and mitigation for critical events."

In addition, other projects funded under the DDDAS umbrella deal with process planning management, critical infrastructure, emergency response and emergency medical services (e.g. *Synthetic Environment for Continuous Experimentation*,; *Hourglass: An Infrastructure for Sensor Networks*; *Dynamic, Simulation-Based Management of Surface Transportation Systems*; *Dynamic Real-Time Order Promising and Fulfillment for Global Make-to-Order Supply Chains; A Data Driven Environment for Multi-physics Applications; Data Dynamic Simulation for Disaster Management (Fire Propagation); Building Structural Integrity*; *An Adaptive Cyberinfrastructure for Threat Management in Urban Water Distribution Systems*). These projects are motivated through different application areas. However the capabilities and inputs developed in these kinds of projects are relevant to decision support systems such as for emergency response and mitigation, and as such they can also be deployed for events like Katrina. Eventually the suite of the technologies developed under these projects can be put together to enable end-to-end, prediction, impact, response and mitigation for critical events, like natural and man-made disasters.

"… new methods and technological infrastructure, including a prototype disaster response test bed which combines an actual evolving crisis event in-tandem with a simulation framework where the on-going event data are continually and dynamically integrated with the on-line simulations. …. Agent-Based Modeling and Simulations approaches …. are a core approach for these kinds of simulations….. "

For example, the project (*Synthetic Environment for Continuous Experimentation*) develops new methods and technological infrastructure, including a prototype disaster response test bed which combines an actual evolving crisis event in-tandem with a simulation framework where the on-going event data are continually and dynamically integrated with the on-line simulations. In eventually deploying such systems will provide the ability for decision support and crisis management of real situations as well as more effective training of first-responders. The computational aspects of the framework developed under this project are built using peer-reviewed published models, driven and validated by real world data. The framework encompasses data and models from public domain, such as Census data, GIS data (street networks, buildings, topography, surrounding farm lands, etc.) from geospatial databases, fire-models, models for blast-explosives-impact dynamics and structural failure, models of building structures under stress, and models of wind and other environmental influences, models for radiological transport and health-economic consequence risk assessments. Real-time sensor data, video streams, and human inputs from the actual or exercise scenarios can be bridged to the virtual environment. Agent-based emergency response simulations can dynamically invoke models, such as the above, to represent a given scenario and also they encompass agent modeling of model human behavior including cultural and other region (or sector) specific characteristics. All this information and data - real-time, historical, and computed/synthetic - may be transmitted to first responders, local, state, and federal government agencies, industry, non-governmental organizations, citizens, and the media coordinate a comprehensive plan for responding to the crises, minimizing this event's impact, and assisting in the recovery from a crisis event.

Furthermore such approaches have relevance to other areas. *Agent-Based Modeling and Simulations (ABMS)* approaches which are a core approach in the above referenced example, are well suited for social science objectives such as how interactions among multiple individual entities generate macro-level outcomes, in ways discussed hereby. ABMS is the computational study of complex systems comprising multiple interacting agents. The agents are software entities whose behavior is determined in part by internal rules and in part by external forces. The agents can represent any persistent real-world entities. For example, agents might represent people (consumers, producers, voters), social groupings (firms, families, communities, nations), institutions (legal systems, governments), biological entities (crops, forests), or physical entities (highway systems, transmission grids, or weather). ABM could potentially embody DDDAS principles in two respects, "in the small" and "in the large." First, agents in ABM social science applications can be configured to have cognitive capabilities enabling learning based on internal deliberations and external observations. Such agents are effectively DDDAS agents "in the small," in the sense that they can deliberatively change their measurement and observation modes on the basis of new information received. Any ABM application incorporating such cognitive agents is intrinsically a DDDAS. Second, an ABM agent can be configured with the particular attributes and behavioral methods of a real-world referent. (For example, an ABM stock trader can embody the trading strategies of an actual stock trader as determined by empirical or laboratory observations; and an ABM stock market can be designed to embody the salient features of an actual stock market.) The ABM agent then becomes, in effect, the virtual embodiment of this real-world referent. Alternatively, the real-world referent can literally replace the ABM agent through an appropriately designed graphical user interface, thus permitting this real-world referent to act within the virtual world as the world develops over time. These ABM capabilities thus permit data streaming within an ABM application through either the virtual or literal embodiment of real-world processes. The connection with DDDAS "in the large" arises if these ABM capabilities are used in support of an *Iterative Participatory Modeling (IPM)* process, thus permitting the form of this data streaming to adapt over time. This process involves the repeated looping through four stages of analysis: Field study and data collection; role-playing games; agent-based model development; and intensive computational experiments. "Role playing games" refers precisely to the two kinds of data streaming previously outlined: application stakeholders can participate in the design of their modeled counterparts; and application stakeholders can participate actively and dynamically in model simulations through immersion by means of an appropriately designed graphical user interface. The repeated looping aspect of IPM then helps to ensure that input from both application stakeholders and researchers will be used in iterative and interactive fashion to revise the data-collection process as well as the form of the model.

"DDDAS agents "in the small," in the sense that they can deliberatively change their measurement and observation modes on the basis of new information received …. "

The two examples of funded projects that are elaborated above and which originated independently, have a number of common research technology areas; for example in application models involved, but also in application composition technologies, in data management, in systems software, in user interfaces systems. Furthermore the capabilities developed can be deployed in tandem thus increasing the impact of the work developed in the individual projects. This last aspect is also the case for many other projects, and the workshop provided opportunity for such discussions to commence among various researchers.

"…funded projects … which originated independently, have a number of common research technology areas… in application models involved, … in application composition technologies, in data management, in systems software, in user interfaces systems… "

Supporting the runtime of such dynamically invoked computations requires advanced systems software that seamlessly integrates heterogeneous platforms: from the real-time data acquisition, and data mining of archival data, to computational grids and other high-end and low-end workstations, to hand-held end-user devices. Runtime technologies needed range from optimized partitioning and mapping of the various component models of the application, depending on the underlying platforms and other resources (like bandwidth, storage, etc), data processing, transfer and management systems, and software frameworks that coherently support such complex environments. More details on the challenges, opportunities, and research efforts pursued under the presently launched projects are discussed in a subsequent subsection. While the discussion above was centered in the two examples of projects, many of the projects mentioned in the beginning of this section and other projects pursue similar frameworks.

"…DDDAS… .. goes beyond the previous approaches… DDDAS concept is more general and extends well beyond methods such as data assimilation…"

DDDAS represents an important nexus between models and data. The dynamic interaction between measurements and application models, with the objective on one hand of making the application modeling processes more accurate, and on the other hand, making the measurement process more effective, goes beyond the previous approaches. For example, the DDDAS concept is more general and extends well beyond methods such as data assimilation, which have been around for some time. DDDAS can be applied in a number of important ways in modeling, and one of the compelling features of DDDAS is that it provides an effective and systematic means of dynamically incorporating data into the executing simulation. In addition the measurement steering component is a key aspect of DDDAS and a major advance in measurement methods and in data management. The data measurement steering component is a unique feature of DDDAS systems and further research and technology development is required to enable such capabilities.

"…Instruments, sensors, databases, human inputs and other devices for taking measurements; data quality assessment, data formatting, and feature extraction; and data measurement steering. In DDDAS environments these … are … linked with numerous feedback loops,.."

The measurement system consists of several components: Instruments, sensors, databases, human inputs and other devices for taking measurements; data quality assessment, data formatting, and feature extraction; and data measurement steering. In DDDAS environments these components are all closely linked with numerous feedback loops, and they are all strongly impacted by the underlying application, system software, and algorithms. In DDDAS environments, data challenges will be driven by the need for the capability to perform dynamic data measurement as well as dynamic data inputs to models, and ability to incorporate measurement data from completely new data sources. Important issues to address in such systems include: on-demand data collection and management, data streaming into the simulation, data representation, data models and congruence of data, real-time constraints, data processing/preprocessing, data collection rates, consumption rates, available bandwidths and other resources and how to discover, obtain, establish the authenticity and correctness and how to maintain an audit trail.

"…basic enhancements in the design, efficiency and sensitivity of measurement instrumentation as a result of technology or a result of the learning process of the DDDAS functioning system, are continually sought…"

The measurement devices collect raw data from a variety of sources. Because of the nature of measurement instrumentation, unexpected failures due to mechanical problems or human intervention are possible. Likewise, basic enhancements in the design, efficiency and sensitivity of measurement instrumentation as a result of technology or a result of the learning process of the DDDAS functioning system, are continually sought. One primary area concerns issues of power. If the measurement device runs on battery, for example, limitations such as battery lifetime, bandwidth, battery draw as a function of load, and reliable function in extreme conditions, are all targets of errors, uncertainties in measurements, and/or failure. Overall cost of the measurement device can also become an issue depending on the nature of the device, and the number and density required.

The next component of the measurement system is central to the state of the raw data that is collected directly from a measurement device. While the data could in principle be of the correct form for modeling, in many cases, due to a variety of experimental limitations and established collection procedures, some pre-processing may be necessary. Several data conditions need to be considered here, including:

- Uniformity: data collections from different instruments will show variances.
- Format: collections taken across different instrument types can range in format and units.
- Noise: percentage of noise in data collections can vary across measurement devices.
- Time stamps: relevance tags and error bars need to be associated with measured data.
- Failure: diagnostics must be in place to establish instrument/measurement failures.

The measurement steering strategy must be tailored to both the application and the measurements available, which can be categorized as static, dynamic, and adaptive control of instruments and sensor networks. For static networks, for example sensing steering can be used to change key sensor properties to trade off the rate that the environment is observed by a network of sensors vs. the power consumed

"…The DDDAS framework enables observational probes (stationary and mobile) such as UAVs, AUVs, and buoys, to form self-organizing reactive observing systems that enable distributed on-demand sensing…"

(*Dynamic Sensor Networks - Enabling the Measurement, Modeling, and Prediction of Biophysical Change in a Landscape*); and the direction that distributed arrays of telescopes are pointed to track transient astrophysical sources (*Real-Time Astronomy with a Rapid-Response Telescope Grid*); or the phased radar arrays can be steered by the executing simulation model to monitor specific aspects and areas tornadic activity. Mobile sensor platforms linked by communication networks can be used to change the location and temporal/length scales over which measurements are taken. The DDDAS framework enables observational probes (stationary and mobile) such as UAVs, AUVs, and buoys, to form self-organizing reactive observing systems that enable distributed on-demand sensing (several projects have started addressing such issues). Examples include using the DDDAS framework to (1) tighten the coupling between the weather forecasting and the design of the aircraft sensor flight plans by reducing the timescales and embedding the data-driven decision making onboard the vehicles (*Coordinated Control of Multiple Mobile Observing Platforms for Weather Forecast Improvement*); (2) actively deploy a combination of fixed and floating sensors to rapidly identify micro-organisms to predict the onset of algal blooms (*A Generic Multi-scale Modeling Framework for Reactive Observing Systems*); and (3) direct the measurements from AUVs to more accurately predict the ocean state and uncertainties in real-time (*Multiscale Data-Driven POD-Based Prediction of the Ocean*). Adaptive networks can be used to change the types of measurements taken, such as in case of CCD-based imaging systems adaptively focus the analysis of a image to different regions depending on the camera CCD imaging substrate, or using adaptive optics to directly modify a mirror such as those deployed in today's state-of-the-art large astronomical telescopes, multicue tracking of objects with many degrees of freedom (*Stochastic Multicue Tracking of Objects with Many Degrees of Freedom*). DDDAS enables new applications, such as updating (during surgery) 3D in-situ MRIs in real-time (*A Novel Grid Architecture Integrating Real-Time Data and Intervention During Image Guided Therapy*), and adaptively changing the measurement grid (NEXRAD and phased radar arrays) to track the severe local weather patterns over CONUS (*Linked Environments for Atmospheric Discovery (LEAD)*).

Measurement steering must determine what, where, and how to obtain the data; this is a real-time resource allocation problem, that also requires performing a cost/benefit analysis. Data collection steering must directly determine what data to collect from the available sources, which in turn requires the ability to assess the relative value of the measurements and information available. For complex large-scale systems, this can be a very indirect process because it is often difficult to determine what needs to be measured, and how to relate the information extracted from the available sensors to the system dynamics of interest; the dynamicity involved may require invoking appropriate models of how the sensors interact with the system. DDDAS extends the state of the art by tightly integrating the data requirements and the application-level models into this decision making process.

"…DDDAS can have major impact on the development and support of instrumentation infrastructure efforts, …"

DDDAS can have major impact on the development and support of instrumentation infrastructure efforts, as for example the (*Dynamic Sensor Networks - Enabling the Measurement, Modeling, and Prediction of Biophysical Change in a Landscape*) project can provide insights on the proposed NEON infrastructure. Another new potential opportunity is in the context of the DANSE (Distributed Data Analysis for Neutron Scattering Experiments) neutron scattering facility providing measurement infrastructure to numerous communities, ranging from biological to basic physics and materials. Specifically for DANSE provides the infrastructure for neutron scattering research. This involves the production of neutron beams at large national facilities, while experiments are performed by small teams who bring their own samples to these facilities for a few days or weeks of beam-time. This research community spans from biology through basic physics, and includes numerous science subfields. From data acquisition through data analysis and identification of trends, computing is an important part of all this neutron scattering research, and advances in computing will elevate the level of science in neutron scattering research. This aspect has been recognized in setting-up the DANSE infrastructure. The underlying technology of DANSE is a runtime framework with interchangeable software components -- an architecture that is well suited for developing and implementing DDDAS applications.

The project investigating laser cancer treatment is similar in many ways. In that project online patient information, including MRIs and tissue data (tumor properties, cell damage data, HSP kinetic data, nano-shell data, etc.) are used along with finite elements models to predict temperature, HPS expression and cell damage, to form a distributed adaptive control system to manage pre-treatment planning, for dynamic real-time control during laser surgery and for post-treatment monitoring.

"…support dynamic assimilation of data and from varying numbers and classes of sensors… dynamically compose simulation components, … dynamic composition … involve metadata management schemes, …. semantic functional and performance oriented data service interfaces … workflow scheduling and management schemes…"

DDDAS applications frequently involve the dynamic choice of algorithms. Different physical, engineering, biological, economic or social science models may be employed and the ability to dynamically compose and couple different components is a common theme in DDDAS applications. Another related common theme is the need to support dynamic assimilation of data and from varying numbers and classes of sensors. The need for and ability to dynamically compose simulation components, to support dynamic choice between different simulation models and on-demand real-time sensor data assimilation requirements pose substantial systems software challenges. Approaches to dynamic composition are likely to involve metadata management schemes, development of schemes for supporting semantic functional and performance oriented data service interfaces along with workflow scheduling and management schemes.

"…unique requirements … vertically integrated application domain knowledge-based software system as well as horizontal software technologies …"

DDDAS environments present unique requirements and core research challenges from the systems software perspective, as articulated in the solicitation. Further, these projects have already led to the development of a number of solutions, including vertically integrated application domain knowledge-based software system as well as horizontal software technologies that can support a broader class of DDDAS environments, and have started developing some the software technologies to enable and support such environments. Such challenges are articulated in the solicitation, and the following discussion puts them in the context of some of the funded efforts and outlines some of the technologies that are either pursued within the funded projects or were articulated by the current investigators as further research challenges and opportunities:

"… adaptive real time response (hard- or soft-, or both, …)…Systems software … needs to be able to address aspects of performance prediction, performance negotiation, and performance guarantees. …. system level quality of service guarantees..."

Application Driven DDDAS System Software Requirements: DDDAS applications pose a number of unique system software and middleware support requirements. These applications involve an element of adaptive real time response (hard- or soft-, or both, depending on the control task or application phase). Systems software (also referred to as Middleware) used to support DDDAS therefore needs to be able to address aspects of performance prediction, performance negotiation, and performance guarantees. Furthermore, DDDAS environments require system level quality of service guarantees. DDDAS applications typically require multiple computational inputs within sometimes predictable, and sometimes unpredictable, periods of time. The timescales differ from application to application, and possibly for different stages and tasks of a given application. For example, applications involving aerodynamic stabilization and neural control may require millisecond level responses while oil reservoir management may require responses in seconds, hours, days or weeks depending on the nature of the control task. In all of these cases, DDDAS software stacks need to be able to support predictable temporal response to such varying characteristics.

"…Application components need to be designed with "hooks" … allow middleware to answer hypothetical questions about functionality and response time characteristics..."

The need for predictable temporal response behavior has many implications on system software design. Application components need to be designed with "hooks" (sensors and actuators) that allow middleware to answer hypothetical questions about functionality and response time characteristics. For instance, an adaptive multipole-expansion or unstructured mesh -based application component might contain hooks that control the refinement factor, the refinement mechanisms, the problem partitioning granularity, or the partitioning strategy. An application that processes electrical system sensor data might have a hook that controls the choice of the dynamical system model used for modeling network transient characteristics.

System software middleware stacks need to be able to use predicted and measured application/system behaviors and response time characteristics to generate overall performance predictions and to make strategic decisions based on these estimates.

"…DDDAS system software stack should also incorporate application knowledge-based solutions that can enable domain-specific selections and adaptations..."

For example, a DDDAS application involving laser prostate surgery will need to carry out intra-operative estimates of temperature distribution. These estimates need to be available while surgery proceeds. Furthermore, the application may have several algorithms used to generate temperature distribution estimates. In addition, the algorithm runtime environment may depend on patient specific data as well as on current state of the computational environment. In this and many other cases a DDDAS application would dynamically choose an algorithm (or choose a parameter such as degree of mesh refinement) based on performance estimates. Finally, the DDDAS system software stack should also incorporate application knowledge-based solutions that can enable domain-specific selections and adaptations; for example knowledge-based systems of application models and application algorithms may be used to enable the dynamic (at runtime) selection of appropriate models and algorithms that are suitable to the available underlying computing, communications and data resources, and that will satisfy potential hard and soft real time constraints of the application requirements or the controlled measurement system.

"…Programming environments and runtime support systems … support development of application components … dynamically choose between different simulation models … dynamically compose models...."

A complex system software stack consisting of middleware and application support components needs to have predictable temporal response characteristics. Programming models, runtime support and application development frameworks need to be constructed to allow support for accurate behavior and performance prediction and need to be constructed to allow programmers to develop, integrate and compose temporally predictable components. Programming environments and runtime support systems need to support development of application components that can interoperate in a manner that allows DDDAS applications to dynamically choose between different simulation models and to dynamically compose models. Composition and interoperability is challenging as models describing the same system may differ in time, and /or space-scales or in computational technique.

Programming models and abstractions need to be able to describe adaptation policy, sensing and actuating hooks and adaptation policies and constraints. While there are limited precedents for this in various communities (e.g. past work in data parallel compilers that support language constructs that allow choice of parameterized data-partitioners, frameworks for computational interactive monitoring and steering), the DDDAS requirements are much broader and more general than current high-performance and grid computing requirements. While efforts exist (e.g. NGS, CSR, NMI, referenced in the DDDAS solicitation), this state of the art needs to be pushed further. Current middleware/systems software cannot robustly support the dynamic requirements of DDDAS environments.

The need to dynamically compose applications as required in DDDAS environments, and to characterize behaviors and predict performance of complex system software and application components, will also drive the development of DDDAS metadata schemas. DDDAS applications will benefit from systematic methods of describing performance and functional information arising from middleware and application components. Descriptions of how function and performance related "hooks" are embedded in applications and manipulated by the system should also be standardized using appropriate metadata schemas.

" … research challenges that penetrate all the layers for the software systems stack..."

DDDAS environments are multidisciplinary and holistic, and are inherently complex, highly dynamic in their behaviors and interactions, involve uncertainty, and enforce time and space constraints on data and resource availability, data transport, computation, and data-driven response. Furthermore, the underlying Grid computing environment is similarly large, complex, heterogeneous and dynamic, globally aggregating large numbers of independent computing and communication resources, data stores and sensor networks. Together, these characteristics lead to unique requirements and associated research challenges that penetrate all the layers for the software systems stack from programming systems to system services and that are not adequately satisfied by existing solutions. Traditional models, technologies and software components have to be extended to address the unique end-to-end application-centric requirements of DDDAS application to allow them to access, assimilate, analyze and process and respond to dynamic data within

the ability to process large volume, high rate data from different sources including sensor systems, archives, other computations, instruments, etc. – the processing has to be dynamically scheduled at the sources, destinations, in-the-network or a combination of these; (2) the ability to deal with dynamic resource requirements and support dynamic allocations, scheduling, instantiation and deployments. (3) support for accessing and visualizing at runtime, computational, measured and sensed data using a variety of portals ranging from high end visualization system, to pervasive handheld devices; (4) support for handling system/application/data unreliability and uncertainty; (5) support for specifying, validating and enforcing adaptation and coupling policies including detecting and resolving conflicts; (6) support for detection of errors and instabilities (e.g., oscillations and infinite loops) and for end-to-end debugging to detect these behaviors.

" … extend Grid services …virtualize the integration of multiple distributed Grids, … computational Grids, data Grids, information Grids, sensors Grids, instrument Grids,…"

System services: System services for DDDAS applications need to extend Grid services to virtualize the integration of multiple distributed Grids, including computational Grids, data Grids, information Grids, sensors Grids, instrument Grids, etc. These services include those that support immediate "just-in-time" dynamic resource co-allocation and co-scheduling, real-time event/data transport, data coupling, event/data logging, system wide time-synchronization, content based notification, communication and coordination mechanisms, element probing and monitoring, policy specification, evaluation and enforcement, specifying, evaluating and verifying quality and provenance of computation and data components, and dynamic time constrained security and trust.

" … autonomic self-adapting software stack …"

Funded DDDAS projects have proposed and implemented innovative system software architectures including both vertically integrated end-to-end environments as well as core crosscutting services. For example, the Instrumented Oil Field project has proposed an autonomic self-adapting software stack that includes a programming system for self-managing DDDAS applications, an autonomic Grid-based execution engine that supports self-optimizing, dynamically adaptive applications based on sophisticated numerical techniques, distributed data management services for real-time data access, exploration and coupling, and self-managing middleware services for seamless discovery, access, interactions and compositions of components, services and data on the Grid. Similarly, the (*Linked Environments for Atmospheric Discovery (LEAD)*) the (*Auto-Steered Information-Decision Processes for Electric System Asset Management*), the (*A Generic Multi-scale Modeling Framework for Reactive Observing Systems*) and other projects are developing similar layered service-oriented architecture frameworks with crosscutting Grid services at the lower layers and domain specific services at the higher levels.

Implications, Outreach and Outlook

The specific goals of the DDDAS program, as stated in the solicitation, are threefold:

- Advancement and propagation of the emerging field of dynamic data-driven applications system research,
- Training of a new generation of interdisciplinary specialists in DDDAS systems, and
- Broad outreach to other relevant sectors so as to create unique opportunities for the sharing of essential knowledge

"… DDDAS approaches are a novel pursuit both in fundamental research and in technology development…"

In contrast to other research and development areas, DDDAS approaches are a novel pursuit both in fundamental research and in technology development. Standard simulation practices typically employ static notions of data infusion and relatively sequential processes, repeated when and if necessary for the scientific endeavor. DDDAS approaches, as illustrative in this document, demonstrate clear benefit over traditional approaches and provide the inspiration for new approaches to complex problems. In addition, many new communities would greatly benefit from DDDAS approaches. Pursuing multidisciplinary research and creating multidisciplinary projects, is a challenge; the setup, execution, and analysis involved in many computational arenas, in particular when they involve more than one