

AFRL-IF-RS-TR-2006-344
Final Technical Report
December 2006



AGENT-BASED COMPUTING INTEGRATION AND TESTING

BBN Technologies

Sponsored by
Defense Advanced Research Projects Agency
DARPA Order No. K536

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REPORT DOCUMENTATION PAGE				<i>Form Approved</i> OMB No. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Washington Headquarters Service, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington, DC 20503.					
PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.					
1. REPORT DATE (DD-MM-YYYY) Dec 06		2. REPORT TYPE Final		3. DATES COVERED (From - To) Jun 00 – Jan 06	
4. TITLE AND SUBTITLE AGENT-BASED COMPUTING INTEGRATION AND TESTING				5a. CONTRACT NUMBER F30602-00-C-0178	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER 62301E	
6. AUTHOR(S) Michael Dean				5d. PROJECT NUMBER DAML	
				5e. TASK NUMBER 00	
				5f. WORK UNIT NUMBER 07	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) BBN Technologies 1300 North 17 th Street, Suite 600 Arlington Virginia 22209				8. PERFORMING ORGANIZATION REPORT NUMBER N/A	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Defense Advanced Research Projects Agency AFRL/IFSE 3701 North Fairfax Drive 525 Brooks Rd Arlington Virginia 22203-1714 Rome NY 13441-4505				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSORING/MONITORING AGENCY REPORT NUMBER AFRL-IF-RS-TR-2006-344	
12. DISTRIBUTION AVAILABILITY STATEMENT APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED. PA# 06-785					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT The DARPA Agent Markup Language (DAML) program developed technology to enable the vision of a Semantic Web, where computers and software agents can discover, understand and exploit disparate data across the World Wide Web in response to a human query. DARPA has provided the leadership and the first crucial steps toward this vision as evidenced by the emerging international standards and technology transition examples initiated under this program. The facilitation, collaboration and sharing of technology across an international research community was critical to the success of DAML, and its successor, the Ontology Web Language (OWL). Like the Semantic Web vision, the work described in this report involved leveraging data physically positioned throughout cyberspace via the World Wide Web (WWW). A very significant portion of the DAML program was conducted on the WWW. Accordingly, the thousands of artifacts evidencing progress and transition are also accessible via the web. This report documents activities and accomplishments under the primary integration and testing contract of the DAML program, along with many live links to underlying standards, documents, tools, tutorials, applications and data artifacts which comprise the bulk of the program legacy and the seeds for future growth of the Semantic Web.					
15. SUBJECT TERMS DAML, OWL, Semantic Web, Mark-up, XML, Ontologies, DARPA Mark-up Language					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT UL	18. NUMBER OF PAGES 25	19a. NAME OF RESPONSIBLE PERSON Dale W. Richards
a. REPORT U	b. ABSTRACT U	c. THIS PAGE U			19b. TELEPHONE NUMBER (Include area code)

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Introduction

1.1. DARPA Agent Markup Language (DAML) Program

At the turn of the 21st century, the modern information technology world was a dynamically changing environment with an exponentially increasing ability to create and publish data that rapidly swamped human abilities to process that data into information. Tim Berners-Lee's original vision for the World Wide Web, as articulated in his 1999 book *Weaving the Web* helped to clarify the problems and the opportunities of these trends. Other researchers were also beginning to understand the benefits of making the vast amount of information currently available on the World Wide Web more accessible to intelligent agents and other computer programs. Agent based computing was seen as a potential solution for recognizing complex patterns in this widely distributed, heterogeneous environment. Unfortunately, there were no standards or commonly accepted methods for marking-up data to enable discovery and/or semantic understanding of that data by software agents across communities of interest.

DARPA's DAML program began in 2000, under the leadership of Professor Jim Hendler, with its primary mission being to create technologies that would enable software agents to dynamically identify and understand information sources, and to provide interoperability between agents in a semantic manner. The DAML program represents one of the critical first steps toward realizing the vision of "The Semantic Web."

To achieve its goals the DAML Program pursued the following objectives:

- Create an Agent Mark-up Language (later referred to simply as DAML) built upon the eXtensible Mark-up Language (XML) that allows users to provide machine-readable semantic annotations for specific communities of interest.
- Create tools that embed DAML markup on web pages and other information sources in a manner that is transparent and beneficial to the users.
- Use these tools to build up, instantiate, operate, and test sets of agent-based programs that markup and use DAML.
- Measure, via empirical experimentation, the productivity improvements provided by these tools.
- Apply these tools to third party agent development, military-specific problems, and support for the intelligence community so as to evolve DAML technologies towards large-scale use.
- Transition DAML to the commercial and military markets via partnerships with industrial and defense-related organizations, primarily in the areas of Command & Control and Intelligence (C2I).

1.2. *BBN Technologies Role*

BBN's role in the DAML Program was to lead the integration and testing of the research and development efforts for the larger DAML team of university and contractor researchers. When this effort was initiated in the summer of 2000, the primary objective of was to develop a flexible framework to facilitate the integration, testing, demonstration and transition of technology components that use the DARPA Agent Markup Language (DAML).

BBN's tasking under this contract was focused five key areas, described below. Each of these areas progressed in parallel. A timeline has been included as Appendix A to this report to help provide chronology to the activity descriptions discussed in the remainder of this document.

1. **Project Engineering:** Develop a framework for community-of-interest development and collaboration of Semantic Web technologies aimed at establishing international standards for realizing an enabling agent markup language. This area included chairing, co-chairing and/or general participation in multiple, internationally supported communities-of-interest working groups, as well as development, documentation and management of face-to-face and web-based technology sharing environments to support community collaboration.
2. **Testing and Experimentation:** Establish a testing environment, develop plans for and conduct Integrated Feasibility Experiments (IFE) and Technology Integration Experiments (TIE). The TIEs were principally aimed at proof of concept experiments in domains relevant to other ongoing DoD research areas such as the AFRL Joint Battlespace Infosphere (JBI) initiative.
3. **Transition:** Identify potential transition customers within DoD for DAML technology insertion and work with those customers to define proofs of concepts and follow-on transition plans. This area also included significant efforts in support of research communities-of-interest to create developer tools and tutorials for learning and applying emerging technology. The benefits of these efforts were further capitalized through the development and maintenance of Open Source web sites for research collaboration and technology transition throughout the Semantic Web communities-of-interest.
4. **Software:** Ensure all software and documentation developed under this program is delivered to the end user, and to the research community as appropriate. The Open Source web sites were the primary mechanism for fulfilling this requirement.
5. **Status Reporting and Documentation:** Develop and track plans for testing, experimentation, transition activities and lessons learned. Progress and results under this area were reported to DARPA and, where appropriate, to the relevant communities-of-interest. This was accomplished through a combination of written reports, formal briefings, web-based news venues and organized technology exchange conferences for the communities-of-interests.

2. Activities and Accomplishments

While there were many, many individual achievements made over the course of the DAML Program, the central accomplishment was the high level of collaboration attained by the United States and international research communities. Together, these communities-of-interest achieved great progress in advancing both the science and the standards required to achieve the promise of the Semantic Web.

The remainder of this document presents highlights of activities and accomplishments under the DAML contract. Detailed artifacts relating to all of the following discussions can be found at one or both of the primary collaboration web sites, <http://www.daml.org> and <http://www.semwebcentral.org/>, created and maintained by the BBN DAML Team during the program. These web sites are rich with documents, code and discussion artifacts detailing much of the history of international efforts to advance Semantic Web concepts and standards from the late 1990s through today. Though originally maintained by BBN under this contract, these sites are now maintained by the Worldwide Web Consortium (W3C), which has committed to providing persistence of the subject contents.

2.1. *Community Support and Integration*

The DAML program started with 16 sponsored (funded, at least in part, by DARPA) teams and grew to 23 over the course of the program. The composition of the teams spanned both organizational and international boundaries. A list of most of these sponsored teams and their primary area of interest is available at <http://www.daml.org/researchers>. In addition to the sponsored teams, BBN also worked closely with a number of European Union collaborators, as well as the at-large open source development community.

As lead integrator for the overall DAML Program, a major component of BBN's effort involved facilitation and coordination among a broad spectrum of domestic and international universities and commercial research organizations. This section of the report introduces eleven of the methods and forums used to achieve the high levels of collaboration exhibited on this program.

2.1.1. DAML.org

With a few weeks of contract award, www.daml.org was launched to establish the program's presence on the World Wide Web and to foster collaboration among the distributed teams. Throughout most of the program, this web site remained the number 3 or higher Google™ hit for "DARPA"; behind only the DARPA home page and the DARPA Grand Challenge robotic car race page. This web site hosted the predecessors of many of the most widely used Semantic Web tools and services existing today.

In keeping with the overall theme of advancing the concepts of the Semantic Web, an early decision was made to use XML to represent most of the data on the site, originally using Apache Cocoon. Much of the site content was re-generated nightly from data maintained in a Concurrent Versions System (CVS) repository using XSLT or from databases.

One of the main goals of the www.daml.org collaboration web site was to promote sharing and re-use of DAML+OIL and later OWL ontologies. For this reason, the site included an uncurated Ontology Library <http://www.daml.org/ontologies/>. This library eventually grew to 282 ontologies before it was replaced by the establishment of the W3C's Ontaria server.

The www.daml.org site also hosted the DAML Crawler <http://www.daml.org/crawler/>. Seeded by the Ontology Library and user submissions, the crawler soon identified over 5.9 million statements on over 21 thousand pages. This initial DAML Crawler was a proof of concept capability only and not sufficiently robust or scalable enough to keep up with rapidly growing web content. This pioneer DAML Crawler was eventually replaced by University of Maryland, Baltimore County's (UMBC) Swoogle, and similar services as the Semantic Web tools and standards matured.

The DAML Tools page <http://www.daml.org/tools/> hosted an uncurated list of Semantic Web tools. It grew to 88 DAML+OIL/OWL-specific tools and 243 total tools before the tools collaboration function was moved to the newer OpenSource collaboration site, <http://www.semwebcentral.org>, also maintained by BBN.

Other resources maintained on the <https://www.daml.org> web site included a list of upcoming events, DAML publications, and a list of general-purpose and domain-specific Semantic Web data sources. Additionally, a DAML Program private site, <https://www.daml.org>, was established and protected using PKI certificates and SSL. This private site was only lightly utilized as a result of the DARPA decision to make as much as possible of the program information public. The generally low adoption rate of PKI technology also limited the utilization of this aspect of daml.org.

Throughout the program period of performance, www.daml.org adopted many 'best practices' from W3C, including datespace naming, adherence to a "cool URIs don't change" mantra, and content negotiation. We also used the W3C Slidemaker tool for many of the briefings hosted there. At the conclusion of the DAML program, the domain name and a static snapshot of www.daml.org were provided to the W3C so that it could be hosted at MIT and remain available to the various communities of interest.

2.1.2. DAML Lab

Early in the program, BBN established the DAML Laboratory at the DARPA Technology Integration Center (TIC). The DAML Lab provided a central set of computing resources for the DAML program. It hosted web servers, several development workstations, a firewall, and a wireless LAN for visitors. Collaboration was supported through WWW servers, archived email lists, and Internet Relay Chat (IRC). Email and DNS servers were maintained on a separate host outside the firewall, for security reasons.

Software was managed in a CVS repository. Most program development was distributed, taking place at performer sites and/or over the World Wide Web.

By December, 2001 rising costs in the DARPA TIC facility became an issue, forcing the DAML Lab capability to be relocated to the BBN-Rosslyn facility in Arlington, VA. BBN hosted and maintained the lab services there for the remainder of the DAML Program.

2.1.3. Joint Committee

At the start of the DAML Program, there were large government sponsored ontology based research programs being conducted in both the United States and Europe. It was clear that an effort to align United States (DAML) and European Union Ontology Inference Layer (OIL) ontology language definition efforts would better facilitate progress toward international standards in this area. In October of 2000 Jim Hendler and Hans-Georg Stork, the corresponding government program managers, created a joint working group including researchers from both programs. Mike Dean, the principal investigator from BBN on this effort, was asked to chair the group. The group was formally known as the Joint US/EU ad-hoc Agent Markup Language Committee, but was more commonly referred to as the “Joint Committee.” The Joint Committee was later expanded to include participants from Canada.

The Joint Committed started with the DAML-ONT language design and produced a combined language named DAML+OIL by leveraging the contributions of both communities. A subsequent revision added support for XML Schema datatypes and was submitted to W3C as a Member Submission in September 2001, for use by the W3C Web Ontology (WebOnt) Working Group. Several Joint Committee members subsequently participated in the WebOnt Working Group and the resulting Web Ontology Language (OWL) closely matches the features found in the original DAML+OIL submission.

With the ontology language effectively transitioned to W3C, the Joint Committee turned its attention to the issue of “query” and produced the DAML Query Language (DQL). Regrettably, DQL never became a W3C Member Submission itself, but likely had some influence on the SPARQL Protocol And RDF Query Language (SPARQL) subsequently produced by the W3C Data Access Working Group (DAWG) as that working group also contained members from the DAML community.

Next, the group turned its focus to using rules to increase the expressiveness of the ontology language. Benjamin Grosz of MIT Sloan played a key role in these efforts, and several new members joined the Joint Committee, particularly from the RuleML Initiative. The committee ultimately developed the Semantic Web Rule Language (SWRL) based on combining OWL and RuleML. A subsequent revision of SWRL added support for built-in operators and functions. This version became a W3C Member Submission in May 2004. SWRL has been widely used and implemented and has emerged as the de facto language for Semantic Web rules.

At the May 2004 DAML PI Meeting, several researchers expressed concern that SWRL still wasn’t expressive enough to describe Semantic Web Service process models. This led the Joint Committee to develop a proposal for a SWRL Extension to First-Order Logic (SWRL FOL). This also became a W3C Member Submission in April 2005, but had not yet been widely implemented by the end of the DAML Program.

Members of the DAML community lobbied hard for a W3C Semantic Web Rules Working Group. This culminated in the W3C Workshop on Rule Languages for Interoperability and the new W3C Rules Interchange Format (RIF) Working Group was established in November 2005. Both the workshop and the working group included a number of participants from the Joint Committee. Additionally, both SWRL and SWRL FOL are cited in the RIF Working Group Charter.

More information on the Joint Committee, including a list of members, is available at <http://www.daml.org/committee/>.

2.1.4. Semantic Web Services

The DAML Services Coalition was formed early in the DAML program by a number of teams interested in Semantic Web Services. It ultimately produced a series of DAML-S and OWL-S releases, as well as numerous publications. OWL-S became a W3C Member Submission in November 2004.

The group that came to be known as the Semantic Web Services Initiative (SWSI) was formed following discussions at the 2002 International Semantic Web Conference (ISWC2002) to align the US and EU efforts in Semantic Web Services, as the Joint Committee had for ontology languages. SWSI was composed of a Language Committee and an Architecture Committee. Mark Burstein of BBN co-chaired the Architecture Committee. Mike Dean, also from BBN, was an active member of this committee. The SWSI efforts eventually led to the Semantic Web Services Framework Member Submission to W3C in September 2005. It was originally expected that SWSI would supplant OWL-S, but it never reached the same level of maturity.

The W3C held a Workshop on Frameworks for Semantics in Web Services in June 2005. New W3C Working Groups or other efforts in this area are expected, but were not announced prior to the end of the DAML Program.

More information on DAML activities in support of Semantic Web Services is available at <http://www.daml.org/services>.

2.1.5. World-Wide Web Consortium (W3C)

W3C work on the Semantic Web pre-dated the DAML program and helped inspire the vision for the program's goals. When the DAML program was launched, the W3C was a key partner and funded participant.

The W3C created the Resource Description Framework (RDF) Core Working Group to update the 1999 RDF Recommendation and move RDF Schema beyond Candidate Recommendation status. Mike Dean participated as an Invited Expert and representative of the DAML program.

The W3C created the Web Ontology (WebOnt) Working Group in August 2001, chaired by Jim Hendler at the University of Maryland. WebOnt was chartered to build an ontology language on top of RDF, based on DAML+OIL. Mike Dean again served as an Invited Expert. He also served as an editor for the Web Ontology Language Reference (OWL), which was initially based on the DAML+OIL specification.

2.1.6. SONAT

Although a series of annual Integrated Feasibility Experiments (IFEs) had been included in the initial vision for the DAML proposal, Jim Hendler, the DAML DARPA Program Manager, decided to run the early portion of the DAML program in a more decentralized fashion, “letting a thousand flowers bloom,” as it were.

Murray Burke became DARPA’s DAML Program Manager in September 2001. Motivated by DAML becoming part of the new DARPA Information Exploitation Office (IXO), Murray identified the requirement for an integrating application that would show military value in the sensor and targeting domains of greatest interest to IXO. The DAML Program ultimately decided to focus on supporting Operational Net Assessment, then part of Joint Vision 2020, and began development of the Semantic Operational Net Assessment Tool (SONAT).

Through the process of establishing a concept of operations for SONAT, BBN developed many of the data integration principles employed in later systems. These included:

- Developing or exposing data sources independent of the target application, to promote reuse
- Adding properties to existing instances (e.g. countries), rather than creating new instances, to ease management and linkage
- Continuing to access instances at their original location and with their original URIs, rather than copying data, to avoid duplication and inconsistencies
- Linking instances into the domain ontology by adding *rdf:type* statements to them, rather than translating all the data

Data gathered in SONAT focused on identifying Elements of National Power (ENP) for countries of interest. As part of the SONAT proof of concept implementation, relevant instances were identified from key data sources and linked into the ENP hierarchy by a periodically-run software agent. Key data sources included:

- FIPS Country Codes (countries)
- NIMA Geonames (natural and man-made features)
- CIA World Factbook (ports and international organizations)
- CIA Chiefs of State (political leadership)
- Defense Joint Transportation Reference Tables (airports)

While most of the Semantic Web community was focusing on Java, we decided to develop the SONAT user interface components using Microsoft's new .NET infrastructure, to increase technological diversity. To integrate the system components, we developed the SONAT Agents architecture <http://www.daml.org/2002/03/agents/>.

DAML+OIL was used to describe agents and to represent the messages passed between them. Agent communication was performed using the CoABS Grid from the DARPA Control of Agent-Based Systems program, in part to align SONAT with the Expeditionary Sensor Grid. The .NET user interface components were connected to the Java agents using a Simple Object Access Protocol (SOAP)-to-CoABS gateway developed by BBN.

SONAT was a truly collaborative effort, for example:

- BBN built the infrastructure and user interface and provided most of the data.
- Dr. Katia Sycara's group at Carnegie Mellon University (CMU) contributed matchmaking technology to assign units to identified targets.
- Dr. Norman Sadeh's group at CMU provided contextually-aware notification services when target priorities changed.
- Lockheed-Martin provided an imagery service for specific targets.
- Yale employed their OntoMerge technology to generate a map representation of targets.
- MIT/W3C's Cwm was used to generate indirect effects.
- The Artificial Intelligence Applications Institute, University of West Florida (AIAI/UWF) Coalition Search and Rescue - Task Support (CoSAR-TS) project used extended SONAT data to identify medical facilities.
- The University of Southern California (USC) Information Sciences Institute (ISI) used WebScripiter to visualize indirect effects.

The resulting SONAT Architecture is depicted in Figure 1.

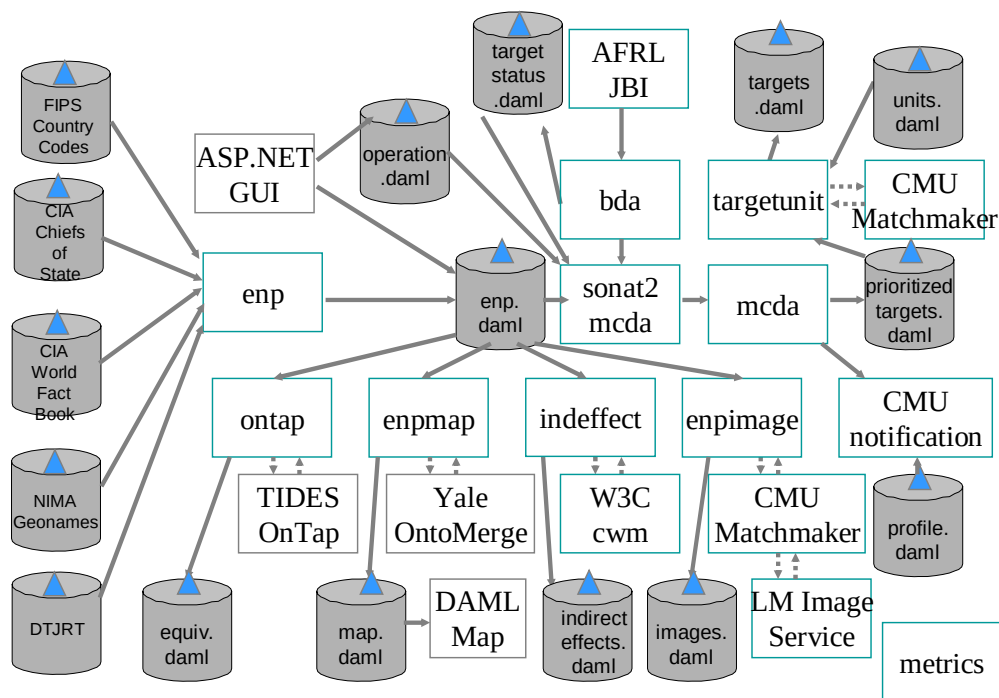


Figure 1: SONAT Architecture

In the summer of 2003, Dr. Mark Greaves assumed responsibilities as DAPRA's DAML Program Manager and with that, the task of mapping the program's final legacy. Under his guidance, the program changed focus to emphasize standards, tools, and transition to operational users. While SONAT did not continue to grow as the central DAML integrating application, many of the concepts explored under the SONAT effort were transitioned to operational problems for a number of DoD transition partners.

Additional information on SONAT is described in the document, “DAML Experiment Plan,” dated June 2002, delivered under this effort; and in the DAML Experiment Briefing presented at the DAML Principal Investigators meeting in October 2002. This briefing can be found at: http://www.daml.org/2002/10/pi-experiment/experiment_files/frame.htm.

2.1.7. RuleML Initiative

The Rule Markup Language (now Rule Modeling Language) Initiative was developed in parallel with the Semantic Web as a means of providing an XML-based rule interchange format. With OWL underway, the Joint Committee started to focus on extending the expressive power of ontologies with rules and a partnership was formed between the DAML program and RuleML. Harold Boley and Said Tabet of the RuleML Steering Committee joined the Joint Committee and Mike Dean joined the RuleML Steering Committee; Benjamin Grosz was already a member of

both. Mike Dean provided RDF and OWL expertise to RuleML. The resulting SWRL language (see paragraph 2.1.3 above) drew heavily from and is compatible with RuleML.

2.1.8. Workshops

The DAML program hosted Principal Investigator (PI) Meetings about every 6 months (see timeline). Schafer Corporation organized the meeting logistics and handled registration. BBN, as system integrator, played a significant role in establishing the agenda, presenting and leading various breakout sessions. Starting with the second PI Meeting, BBN also supported these events with wireless Internet access.

To facilitate technology transition, the DAML program hosted a series of other meetings for current and potential government users of Semantic Web technology. As system integrator, BBN played a significant role in the planning and execution of these meetings. The first three of these events were called the Semantic Web for Military Users Conferences. The conferences focused on informing the DoD and the Intelligence Community on the objectives and progress of the DAML program and other Semantic Web initiatives. Each of these conferences had about 100 attendees. The fourth and final conference of this series was organized in conjunction with the Federal CIO Council's Semantic Interoperability Community of Practice (SICoP). This April 2005 conference was called the Semantic Web Applications for National Security (SWANS) Conference and was attended by a wider US government audience of about 300.

Agendas and briefings for these meetings are available at <http://www.daml.org/meetings/>.

2.1.9. Tool Study

Early during his tenure as DAML Program Manager, Dr. Greaves asked BBN to conduct a survey of available OWL tools. To achieve accurate findings, it was necessary for the assessment to consider a majority of the existing Semantic Web tools available. We started with the tools listed on the DAML Tools page (<http://www.daml.org/tools/>). These included available tools built under the DAML program as well as many tools not funded through DAML. The assessment itself was conducted in the following steps:

1. Define a set of tool categories to allow comparative assessment of like tools
2. Define a set of workflows used by Semantic Web Developers to create Semantic Web ontologies, tools, applications and data. (These workflows helped validate the tool categories and identify gaps.)
3. Assign current tools to the appropriate category based on category definitions.
4. Define global criteria to be used to conduct initial assessment of all tools. A key part of this step is identifying which tools are OWL compatible. Tools that are not compatible with OWL were disqualified and not tested further.
5. Define assessment criteria and use cases for each tool category
6. Conduct assessments on each tool and record results
7. Analyze results and make recommendations to DARPA

Of the initial 88 tools identified for review under this study, only 25 were both OWL compatible and sufficiently mature to undergo standard testing processes. Comparative evaluation of these 25 tools proved to be very insightful in terms of both tool capabilities and in gaps in available tool capabilities in the research community. Results from this effort were delivered in report form as the *Semantic Web Tools Assessment*, dated November 2003. In addition, an interactive version of the report is available on SemWebCentral.org: <http://www.semwebcentral.org/assessment/>.

2.1.10. SemWebCentral.org

For the first three and a half years of the DAML program, www.daml.org was the central collaboration web presence for a significant portion of the Semantic Web research community. As the DAML program entered the transition phase of its life cycle, the DARPA Program Manager tasked BBN with creating a new, user friendly, open source web site aimed at a much broader user base beyond the research community. The main objective of the site was to make it easy for anyone interested in learning about or developing Semantic Web applications to find what they needed. The resulting site, www.SemWebCentral.org, is an open source portal for the Semantic Web community of interest. SemWebCentral is based on GForge, and has been extended to export project information in OWL using the OWL-EL tag library developed for this purpose. It was modeled, in part, after CougaarForge, which had been developed for the DARPA Ultra*Log program to support interest in the DARPA developed Cougaar Agent Architecture.

By the end of the DAML program, www.SemWebCentral.org hosted 100 projects and had over 500 registered users. BBN has since taken responsibility for maintaining www.SemWebCentral.org at its own expense as a service to the community.

2.1.11. Subcontractor Management

As part of our role as integrator for the overall DAML program, and in collaboration with the DARPA DAML Program manager, BBN supported contractual access for a number of DARPA funded research subcontractors under the DAML program. These subcontractors were:

Ian Horrocks

Professor Ian Horrocks of the University of Manchester worked with the US/EU Joint Committee, the Semantic Web Services Initiative (SWSI) and appropriate W3C Working Groups to support development of standards for Semantic Web Rule Language (SWRL). Additionally, Professor Horrocks contributed to the development of tools and components to support OWL applications, in particular support for creating and reasoning with OWL and with the new OWL Rules language. Much of his work was in collaboration with Dr. Peter Patel-Schneider on the development of new proof techniques, algorithms and optimizations for inference in OWL, and in SWRL. Code for the resulting Hoolet tool is available at <http://owl.man.ac.uk/hoolet/>.

Peter Patel-Schneider

Peter Patel-Schneider of Lucent Technologies contributed to the development of new proof techniques, algorithms, and optimizations for inference in OWL and SWRL through collaboration with Ian Horrocks and the US/EU Joint Committee. Additionally, Mr. Patel Schneider conducted work in the design and implementation of improvements to the OWL Parser (OWLP) and description logics-based OWL (OWL DL) parser and processor. The resulting OWLP tool is available at <http://www-db.research.bell-labs.com/user/pfps/owlp/>.

Tom Martin

Mr. Martin of Research Management Enterprises has been associated with the DAML program since its inception, starting as a SETA for the initial DARPA DAML Program Manager. He was later contracted to be the lead organizer and planner for the Semantic Web Applications for National Security (SWANS) conference held in April 2005. In this capacity, Mr. Martin collaborated on behalf of the DAML program with representatives from the Federal CIO Council's Semantic Interoperability Community of Practice (SICoP) to ensure all objectives from that organization were addressed.

North Carolina State University

Professor Munindar Singh and his students at NCSU developed a protocol-based approach for specifying processes based on Web Services. This was subsequently extended to support contexts. Code and documentation for the resulting OWL-P tool is available at <http://projects.semwebcentral.org/projects/owlp>.

InfoEther

InfoEther was the designer and developer for the CougaarForge open source site under the DARPA Ultra*Log program. Their experience was leveraged to quickly and efficiently stand up the premier open source web site for the Semantic Web community of interest. In collaboration with BBN, InfoEther developed and operated SemWebCentral.org until it was transitioned to BBN in January 2006 as the program was winding down.

2.2. Tools Development

BBN developed a number of Semantic Web tools under the DAML program. The major and/or enduring tools are described below.

2.2.1. Validators

At the DAML Kickoff meeting in 2000, Jim Hendler issued a set of homework assignments for each funded team which involved the generation of content using the initial DAML ontology language specification, DAML-ONT. The resulting lessons learned highlighted the need for a program to quickly check content for a variety of common coding and format errors, e.g., mis-typed URIs. Dave Rager of BBN developed the DAML Validator which ultimately included about 50 different checks. The tool can be found at <http://www.daml.org/validator/>.

The DAML Validator was subsequently updated to support OWL and was hosted on a DAML program-server until the end of the project. While the software can still be downloaded from <http://projects.semwebcentral.org/projects/vowlidator/>, many of the OWL developer tools released over the past couple of years have OWL validation built in.

Another DARPA DAML funded tools efforts was called SweetRules. SweetRules is a pluggable set of rules tools for RuleML and SWRL featuring: interoperability between Prolog, production rules, OWL, CommonRules, Jena-2, and several other languages; and inferencing with negation, priorities, and procedural attachments. In conjunction with our SweetRules effort, Dave Kolas from BBN developed a corresponding validator for SWRL, reusing elements of the OWL Validator. Code for the SWRL Validator is available at <http://projects.semwebcentral.org/projects/swrl-val/>.

2.2.2. Dumpont and HyperDAML

BBN developed a simple web-based viewer called ‘dumpont’ to provide an overview of the class and property hierarchies found in a DAML+OIL or OWL ontology. It works in conjunction with HyperDAML, which provides hyperlinked markup of RDF/XML documents. A revision to the original release called ‘dumpont2’ was designed to more efficiently process large ontologies using streaming, and to display more information about cardinality and class restrictions on properties. Code for dumpont2 is available at <http://projects.semwebcentral.org/projects/dumpont/>. Code for HyperDAML is available at <http://projects.semwebcentral.org/projects/hyperdaml/>.

2.2.3. PalmDAML

PalmDAML was developed by BBN as the first viewer for static Semantic Web content downloaded to Personal Digital Assistants (PDAs) running PalmOS. Additionally, BBN investigated use of the wireless capabilities of the then-new Palm i705 device to provide direct access to dynamic content, but concluded that the limited networking and processing capabilities of the device and PalmOS 4.1 were insufficient. Newer devices, particularly those supporting WiFi, are much more capable. PalmDAML and several sample datasets are available at <http://www.daml.org/PalmDAML/>.

2.2.4. DAML DB

DAML DB is a scalable, high-performance persistent store for Semantic Web content. It uses memory-mapped files and is intended to be embedded in other applications or tools. Two extensions and re-implementations of DAML DB were developed under other (non DARPA) funding. The current implementation is being used with the *Sesame* RDF Schema-based repository and querying facility as a front-end on the Common Ontological Data Environment (CODE) transition project under this effort, and Geospatial Semantic Web and other projects. Code for the initial implementation of DAML DB is available at <http://www.daml.org/2001/09/damldb/>.

2.2.5. Object Viewer

The Object Viewer is a dynamic browser for OWL instance data. It was originally developed for SONAT in C# as a custom control for Microsoft ASP.NET and hosted on the www.daml.org web site. A subsequent implementation allowed embedded use in Java applications. The embedded version is used in multiple research programs. Code for the Java implementation is available on SemWebCentral at: <http://projects.semwebcentral.org/projects/objectviewer/>.

2.2.6. Kazuki

Kazuki generates a Java API and implementation classes from a set of OWL ontologies. The latest version is based on Jena2, and provides much easier access to OWL information from Java programs. Kazuki was heavily used by the DAML community until it was subsequently integrated into the Protégé OWL plug-in by its author, Holger Knublauch. Code for Kazuki is available at <http://projects.semwebcentral.org/projects/kazuki/>.

2.2.7. SWeDE

The Semantic Web Development Environment (SWeDE) is an OWL ontology editor and development environment based on the Eclipse Integrated Development Environment (IDE). It is targeted at developers comfortable with RDF/XML, rather than Subject Matter Experts who require a more graphical editing interface such as Protégé. SWeDE has been downloaded over 15,000 times, making it the most popular project on SemWebCentral.org. Code for SWeDE is available for download at: <http://owl-eclipse.projects.semwebcentral.org/>.

2.2.8. SweetRules

As part of the “Tools for Rules” effort, BBN participated in the SweetRules project led by Prof. Benjamin Grosz of MIT Sloan. BBN’s contribution to SweetRules focused particularly on the use of SWRL. Specific contributions included:

- translators between the SWRL XML and SWRL RDF concrete syntaxes
- SWRL implementation for the Jena2 rule engine
- Jena2 implementations of SWRL built-ins,
- Recommendations for integration of a SWRL editing capability into the Protégé ontology editor.

SweetRules code is available at <http://sweetrules.projects.semwebcentral.org/>.

2.2.9. Semantic Web Reference Application

The Semantic Web Reference Application consists of a downloadable, installable and executable package that elucidates key features of the Semantic Web. The system enables a novice user/developer to probe the fundamentals of a basic Semantic Web system and its underlying

code construction. The system includes appropriate documentation and hands-on tutorials. The tutorials serve two distinct levels; the Semantic Web user and the Semantic Web developer.

The reference application demonstrates the following areas:

- Knowledgebase formation from relational databases, web services, and other distributed knowledgebases and ontologies.
- Knowledgebase inference and rules
- Simple and complex knowledgebase queries and validation
- Clear delineation of Semantic Web building blocks, interfaces, and language/query constructs.
- Contrasts between OWL/Semantic Web and HTML/search engine approaches.

The Semantic Web Reference Application and tutorial are available for download at <http://refapp.projects.semwebcentral.org/>

2.2.10. Ocelot

Ocelot is an ontology viewer, combining the features of dumpont and the Object Viewer with summary statistics. It is available as either a servlet or a Firefox browser plug-in.

The Ocelot servlet may be accessed online at <http://ocelot.semwebcentral.org/>. Code for Ocelot is available at <http://projects.semwebcentral.org/projects/ocelot/>.

2.3. Data

In addition to focusing on tools for the DAML program, we realized that the availability of data, particularly generic and domain-specific reference data, was a critical enabler for the Semantic Web. Accordingly, we began to convert various data sets and develop a set of tools and technologies for exposing various forms of data on the Semantic Web. We initially focused on data sets that are complete and authoritative.

We started with information such as the lists of countries maintained by ISO and FIPS. Since a lot of information is publicly available from authoritative data sources only as HTML web pages, we developed our own techniques and tools to support HTML “screen scraping” at <http://www.daml.org/2001/10/html/>. The tools were initially tested against dynamic gateways to obtain information about New York Stock Exchange symbols, US Postal Service ZIP Codes, and airport codes. Additionally the tools have been applied to numerous other static and dynamic data sources, including multiple editions of the CIA World Factbook.

Additionally, a lot of information is maintained in relational databases, and should continue to be so to take full benefit of the inherent support for scalability, transactions, and security. BBN developed a number of servlet interfaces to relational databases, including the Modern Integrated Database (MIDB) used extensively for military targeting. While we appreciate the value of generic interfaces, we have found that large schemas such as MIDB typically include a range of

design patterns that make fully automated generation of high-quality OWL ontologies and/or instance data difficult, and have opted instead to employ custom code.

When OWL replaced DAML+OIL, we undertook the conversion of our data sets, along with the rest of the DAML community. While the basic translation from DAML+OIL to OWL was relatively straightforward, the number of different data sets involved made this a fairly significant effort. A list of Semantic Web data sets made available through the DAML Program, including many developed by BBN, is available at www.daml.org/data/.

2.4. Experiments

Under the DAML program, BBN undertook multiple experiments, investigating how the Semantic Web could enhance other emerging technologies.

2.4.1. CoABS

The CoABS Experiment investigated how DAML-S semantic service descriptions could be applied to the JINI-based CoABS Grid developed under the DARPA Control of Agent Based Systems (CoABS) program. CoABS was originally a sister program of DAML under Jim Hendler's Agent Based Computing umbrella. The demonstration, conducted in the context of the Coalition Agents Experiment (CoAX) successfully used DAML for communication, filtering, and security policies and DAML-S for service discovery and matchmaking.

This experiment demonstrated a number of benefits of using DAML and more generally semantic web technology to enhance the flexibility, power and human control of agent systems. Additionally, this project developed perhaps the first working prototype of a DAML-S grounding for execution of agent communications based on DAML-S service descriptions. In contrast with other grounding models, which were specifically for the web environment, our grounding mechanism translated processes inputs and outputs into Foundation for Intelligent Physical Agents (FIPA) compliant messages with DAML content for communication via the CoABS Grid. As such we have demonstrated the utility of DAML-S for a community other than the web services community.

Also this project was our first opportunity to test and utilize the CMU DAML-S Matchmaker capability in a live demonstration. We developed a set of agent service models, and a set of ontologies for the concepts used to describe the process referenced in those models. We developed tools for client agents to use to interact with the matchmaker (and the CoABS Grid-based one that we developed) to facilitate the interactive discovery of and utilization of discovered services.

Results of this experiment were documented and delivered under a separate report from this effort, *DAML-S and the CoABS GRID: An Experiment Utilizing DAML-S Semantic Service Descriptions for Dynamic Agent Interoperation*, dated March 2003.

2.4.2. Joint Battlespace Infosphere (JBI)

The Joint Battlespace Infosphere (JBI) Technology Integration Experiment (TIE) sought to show how Semantic Web technology could enhance the JBI being developed by AFRL. This work was conducted in 4 phases.

The first phase employed the JINI-based JBI 0.8 implementation to implement the Battle Damage Assessment (BDA) agent in the DAML Experiment (SONAT). This capability was included in the plenary demo at the October 2002 DAML PI Meeting. It employed standard XML rather than DAML+OIL.

The second phase included development of a DAML+OIL ontology for Information Object definitions, a specialized DAML implementation of the JBI 0.8 Application Programming Interface (API) focusing on use of Information Object hierarchies to aggregate publish/subscribe registrations, a test harness showing multiple publishers and subscribers, and a simple demonstration. This work is reported at <http://www.daml.org/2002/11/jbi/>.

The third phase built on the Information Object ontology and evaluated the use of DAML Query Language (DQL), Java Expert System Shell (JESS), Fast Classification of Terminologies (FaCT), and Renamed ABox and Concept Expression Reasoner (RACER) to match Information Objects against subscriptions expressed as OWL classes, using OWL representations of Notices to Airmen (NOTAMS) as Information Objects. JESS proved to be the most efficient. The results of this work was presented at AFRL as <http://www.daml.org/2003/06/daml-jbi/Overview.html>.

The fourth phase integrated the JESS subscription matcher into the then-new JBI JBOSS implementation. This was demonstrated at the October 2003 DAML PI Meeting and during the November 2003 meeting of the Air Force Scientific Advisory Board at AFRL. Under separate DAML tasking, Mike Sullivan (BBN) coordinated a technical group that maintained the JBI Common API (CAPI), in a manner modeled after the Joint Committee. BBN also maintained the JBI web site <http://www.infospherics.org> until it was transferred to AFRL in January 2005.

Results of this experiment were documented in a separate report from this effort, *Joint Battlespace Infosphere (JBI) Technology Integration Experiment*, dated March 2006.

2.4.3. Natural Language

The natural language experiment investigated the use of Semantic Web technology with BBN natural language processing technology developed most recently under the DARPA IPTO Translingual Information Detection, Extraction and Summarization (TIDES) program. The TIDES technology identifies entities including people, organizations, and locations, along with relationships between them, in unstructured text documents.

The experiment involved looking for information about the political leadership of Afghanistan (identified from the CIA Chiefs of State data source previously converted into DAML+OIL for SONAT). The experiment examined 5000 wire service articles for relevant content. We built a

DAML+OIL ontology corresponding to the extracted results, which were stored in a Microsoft SQL Server database. We also built a servlet to generate DAML+OIL statements using the ontology from the database on demand.

The experiment demonstrated the viability of using natural language extraction technology to generate Semantic Web content, but also highlighted some of the limitations of the current state of the art in terms of precision, recall, and co-reference resolution. Some information was obtained that was not readily available from structured data sources. Newswire articles provided a good source of timely updates. The experience gained in this experiment contributed to the subsequent use of the related BBN tools *IdentiFinder™* and *Serif™* in other DAML transition programs.

Results of this experiment were documented and delivered in a separate report from this effort, *English Translation & Automated DAML Markup*, dated March 2006.

2.5. Transition

In addition to the multiple technology transition opportunities afforded by the many technical meetings and conferences, BBN led a number of efforts to transition Semantic Web technology directly to other military and Intelligence Community programs. The following subsections provide brief overviews of some of the unclassified activities.

2.5.1. Center for Army Lessons Learned

We visited the Center for Army Lessons Learned (CALL) at Ft. Leavenworth and assessed the applicability of Semantic Web technology to the catalog of their lessons learned reports, which consisted primarily of unstructured text documents. This led to participation in several Army Knowledge Symposia and to various discussions with the Army Knowledge Online (AKO) portal program after Dr. Rick Morris transferred from CALL to the Army CIO's office. Dynamics Research Corp. provided a DAML+OIL representation of the CALL Thesaurus, which we used as a key dataset for demonstrating PalmDAML.

2.5.2. Navy Warfare Development Command

For the Navy Warfare Development Command (NWDC), we provided a DAML+OIL representation of the Navy Lessons Learned, which included more structured information than their Army counterparts. We also collaborated with Dr. David Aha and Dr. Kalyan Gupta of the Naval Research Lab to annotate the Lessons Learned with additional DAML+OIL information resulting from their natural language extraction work on the textual portions of the lessons learned.

We also supported NWDC and the Navy's Space and Naval Warfare (SPAWAR) Systems Center San Diego in their Expeditionary Sensor Grid (ESG) program. This included developing and presenting a DAML+OIL tutorial and providing a demonstration showing use of DAML+OIL with their weather agent.

2.5.3. Intelink

BBN staff from the DAML Program provided Semantic Web related technical consulting support to the DARPA/Intelink Management Office (IMO) Horus program, a separately funded DAML Integration and Transition effort. The Horus Program was eventually suspended due to funding issues; however, the technical momentum gained helped lead to work on other intelligence community-related programs.

2.5.4. Air Mobility Command

Under the DAML contract, BBN performed initial work on representing portions of the Foreign Clearance Guide (FCG) governing diplomatic clearance requirements for over-flights by US government-owned aircraft. This included development of a DAML+OIL ontology and a calculator for lead-times.

Results of the initial work led to subsequent work under the AFRL Integrated Flight Management (IFM) Advanced Technology Demonstration (ATD). This work focused on creating an OWL representation and supporting tools for the FCG process. This program also included a BBN effort to automatically generate OWL representations of Notices to Airmen (NOTAMS) from semi-structured text using natural language processing techniques.

2.5.5. Joint Warfare Analysis Center

Under the DAML contract, BBN initially developed a Common Ontological Data Environment (CODE) prototype capability for the Joint Warfare Analysis Center (JWAC). This focused on integrating and deconflicting information from a variety of structured data sources. The CODE methodology made significant use of SWRL rules for ontology translation and mapping.

The force multiplier potential of a Semantic Web solution for day-to-day analytical activities was successfully demonstrated at the end of that effort.

3. Summary

The DARPA Agent Markup Language (DAML) program catalyzed the Semantic Web research community, leading to wider interest and collaboration among research programs to work towards common standards, tools, applications, and publications. A major accomplishment was the alignment of what could easily have become 3 different Semantic Web visions among US and European researchers and the W3C. The field has emerged as its own academic discipline, with the Semantic Web Science Association, the International Semantic Web Conference series, two journals, and a number of other regularly scheduled conferences. The technology is being used in a variety of programs in the US military and Intelligence Community, as well as commercial organizations. This effort, with its emphasis on integration and testing, played a key part in meeting DARPA's objectives as outlined in Section 1 of this report.

Appendix A: Timeline

Key events and milestones in the DAML program.

2000

February 7: DARPA BAA 00-07 proposals due
June 22: DAML Integration and Transition contract awarded to BBN; Professor Jim Hendler is DARPA's Program Manager for DAML
July 31: www.daml.org available
August 14-16: Kickoff PI Meeting, Cambridge MA
October 10: DAML-ONT released
October 24: Joint Committee formed

2001

January 11: DAML+OIL released
February: DAML_S (Services) Coalition formed
February 13-15: PI Meeting, Arlington VA
March 27: DAML+OIL (March 2001) released
March 30: W3C RDF Core Working Group formed
April 10: Scientific American feature article "The Semantic Web"
[Berners-Lee 2001]
May 11: DAML Validator initial release
May 30: DAML-S 0.5 released
June 6-7: Semantic Web for the Military User, TIC, Arlington VA
July 18-20: PI Meeting, Nashua NH
August 14: W3C Web Ontology Working Group formed
September 1: Murray Burke becomes DARPA's DAML Program Manager
November 13-14: Semantic Web for the Military User 2, Naval Research Lab, Washington DC
December 5: DAML-S 0.6 released
December 21: DAML Lab moved to BBN Rosslyn office
December 18: DAML+OIL acknowledged as W3C Member Submission

2002

February 12-14: PI Meeting, St. Petersburg FL
April 15-17: Joint EEE/SWMU/GMUG meeting, NUWC, Newport RI
August 29: DQL (August 2002) released
October 11: DAML-S 0.7 released
October 16-18: PI Meeting, Portland OR

2003

January 20: Semantic Web Services Initiative formed
April 1: DQL (April 2003) released
April 8-10: PI Meeting, Miami FL
May 7: DAML-S 0.9 and OWL-S 0.9 released
May 7-8: Semantic Web for the Military User 2003, Reston VA
June 6: Dr. Mark Greaves becomes DARPA's DAML Program Manager
October 16-18: PI Meeting, Captiva Island FL
November 19: SWRL 0.5 released

2004

January 8: OWL-S 1.0 released
February 2: www.SemWebCentral.org available
February 10: W3C OWL Recommendation
April 30: SWRL 0.6 released
May 15: SWRL acknowledged as W3C Member Submission
May 25-26: PI Meeting, New York City NY
November 4: SWRL FOL released
November 10: OWL-S 1.1 released
November 22: OWL-S acknowledged as W3C Member Submission
November 30-December 2: PI Meeting, San Antonio TX

2005

April 7-8: Semantic Web Applications for National Security (SWANA), Arlington VA
April 11: SWRL FOL acknowledged as W3C Member Submission
April 27-28: W3C Workshop on Rule Languages for Interoperability, Washington DC
May 27: Bob Popp becomes DARPA's DAML Program Manager
June 9-10: W3C Workshop on Frameworks for Semantics in Web Services
July 26: OWL-S 2.1 released
September 9: SWSF acknowledged as W3C Member Submission
November 7: W3C Rule Interchange Format Working Group formed

2006

January 13: Michael Pagels becomes DARPA's DAML Program Manager
January 31: DAML program officially ends