KEPUKI D	OCUMENTATION P	AGE	OM8 No. 0704-0188
Autor reporting burgen for this collection of in pethering and maintening the data readed, an (election of information, including supportion from informers, Surfa 2264, antiopren, VA 2220	formation is descripted to everyge 1 hour or is completing and reviewing the collection o is for reducting this burden, to Washington in 2-1302, and to be Office of Management an	Progenes, including the time for f information Sand comments rep indexectors Sanata, Commente for information Sanata, Commente for information Sanata, Commente for	Contering and scholars, startling onesing data saura antang tim burgan atamata ar pre anne apart af th a tentering Contention and America, 1215 articles
1. AGENCY USE ONLY (Leave bla	nk) 2. REPORT DATE	3. REPORT TYPE AN	D DATES COVERED
TITLE AND SURTITLE	12/6/96	Final Report	, 12/15/93 - 10/31/96
Communication and Co	ordination in Multi-A	cont Systems.	F40620 04 1 0000
Agent-Oriented Progr	amming and Computation	nal Social Laws.	r49020-94-1-0090
L AUTHOR(S)			
· Yoav Shoham	L		AFOSD TD OF
			MOSK-1K-9/
Dept. of Co	mputer Science	C	7259
Stanford Un	iversity		
Stanford, C	A 94305		
." SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)			AGENCY REPORT NUMBER
Department	of the Air Force		
110 Duncan	Avenue, Suite B115		
Bolling AFB	, DC 20332-0001		
22. DISTRIBUTION / AVAILABILITY	STATEMENT		126. DISTRIBUTION CODE
12a. DISTRIBUTION / AVAILABILITY Approved for public r	STATEMENT elease: distribution	unlimited.	126. DISTRIBUTION CODE
Approved for public r	STATEMENT release: distribution	unlimited.	126. DISTRIBUTION CODE
Approved for public r	STATEMENT elease: distribution	unlimited.	12b. DISTRIBUTION CODE
Approved for public r	STATEMENT elease: distribution	unlimited.	12b. DISTRIBUTION CODE
Approved for public r 13. ABSTRACT (Maximum 200 wor Agent oriented pro which a programmer is	STATEMENT release: distribution cs; gramming was proposed given the opportunity	unlimited. as a high-level p	126. DISTRIBUTION CODE
Approved for public r Approved for public r Agent oriented pro which a programmer is uniform, high-level 1	statement release: distribution gramming was proposed given the opportunity anguage. Furthermore	unlimited. as a high-level p y to communicate y , the programmerco	12b. DISTRIBUTION CODE programming language, in with other programs in a build explicitly represent
Approved for public r Agent oriented pro which a programmer is uniform, high-level 1 in the program (or 'a	statement elease: distribution gramming was proposed given the opportunity anguage. Furthermore gent') the relationsh	unlimited. as a high-level p y to communicate w , the programmerco ip with other prog	12b. DISTRIBUTION CODE programming language, in with other programs in a buld explicitly represent gram (or 'agent'), includ
Approved for public r Approved for public r Agent oriented pro which a programmer is uniform, high-level 1 in the program (or 'a the beliefs about the was that such 'mental	statement release: distribution gramming was proposed given the opportunity anguage. Furthermore gent') the relationsh other agents and the -level' design would r	unlimited. as a high-level p y to communicate y , the programmerco ip with other prog obligations made	12b. DISTRIBUTION CODE programming language, in with other programs in a buld explicitly represent gram (or 'agent'), includ to them. Our hypothesis
Approved for public r Agent oriented pro which a programmer is uniform, high-level 1 in the program (or 'a the beliefs about the was that such 'mental enable the analysis a	statement release: distribution gramming was proposed given the opportunity anguage. Furthermore gent') the relationsh other agents and the -level' design would p nd even design of comp	unlimited. as a high-level p y to communicate w , the programmerco ip with other prog obligations made provide a powerful plex distributed s	programming language, in with other programs in a buld explicitly represent gram (or 'agent'), includ to them. Our hypothesis abstraction that would systems.
Approved for public r Approved for public r Agent oriented pro which a programmer is uniform, high-level 1 in the program (or 'a the beliefs about the was that such 'mental enable the analysis a In addition to suc	statement release: distribution gramming was proposed given the opportunity anguage. Furthermore gent') the relationsh other agents and the -level' design would p nd even design of comp h coordination via high	unlimited. as a high-level p y to communicate y , the programmerco ip with other prog obligations made provide a powerful plex distributed s gh-level modeling	12b. DISTRIBUTION CODE programming language, in with other programs in a buld explicitly represent gram (or 'agent'), includ to them. Our hypothesis abstraction that would systems. and communication, we were
Approved for public r Approved for public r Agent oriented pro which a programmer is uniform, high-level 1 in the program (or 'a the beliefs about the was that such 'mental enable the analysis a In addition to suc interested in global	statement release: distribution gramming was proposed given the opportunity anguage. Furthermore gent') the relationsh other agents and the -level' design would p nd even design of comp h coordination via hig mechanisms that elimin	unlimited. as a high-level p y to communicate w , the programmerco ip with other prog obligations made provide a powerful plex distributed s gh-level modeling nate the need for	programming language, in with other programs in a buld explicitly represent gram (or 'agent'), includ to them. Our hypothesis abstraction that would systems. and communication, we were explicit coordination in
 Approved for public r Asstract (Maximum 200 wor Agent oriented pro which a programmer is uniform, high-level 1 in the program (or 'a the beliefs about the was that such 'mental enable the analysis a In addition to suc interested in global the place. Specifica and conventions. The 	statement release: distribution gramming was proposed given the opportunity anguage. Furthermore, gent') the relationsh other agents and the -level' design would p nd even design of comp h coordination via hig mechanisms that elimin lly, we borrowed from idea is that just as	unlimited. as a high-level p y to communicate w , the programmerco ip with other prog obligations made provide a powerful plex distributed s gh-level modeling nate the need for everyday experier in real life traf	12b. DISTRIBUTION CODE programming language, in with other programs in a puld explicitly represent gram (or 'agent'), includ to them. Our hypothesis l abstraction that would systems. and communication, we were explicit coordination in the the notion of social 1 fic rules restrict one
Approved for public r Approved for public r Agent oriented pro which a programmer is uniform, high-level 1 in the program (or 'a the beliefs about the was that such 'mental enable the analysis a In addition to suc interested in global the place. Specifica and conventions. The enough to eliminate m	statement release: distribution gramming was proposed given the opportunity anguage. Furthermore gent') the relationsh other agents and the -level' design would p nd even design of comp h coordination via hig mechanisms that elimin lly, we borrowed from idea is that just as ost the need for real-	unlimited. as a high-level p y to communicate w , the programmerco obligations made provide a powerful plex distributed s gh-level modeling nate the need for everyday experier in real life traf -time conflict res	programming language, in with other programs in a buld explicitly represent gram (or 'agent'), includ to them. Our hypothesis abstraction that would systems. and communication, we were explicit coordination in the the notion of social is fic rules restrict one solution while driving but
Approved for public r Approved for public r Agent oriented pro which a programmer is uniform, high-level 1 in the program (or 'a the beliefs about the was that such 'mental enable the analysis a In addition to suc interested in global the place. Specifica and conventions. The enough to eliminate m not so much so as to interested	statement release: distribution gramming was proposed given the opportunity anguage. Furthermore gent') the relationsh other agents and the -level' design would p nd even design of comp h coordination via hig mechanisms that elimin lly, we borrowed from idea is that just as ost the need for real- make any navigational	as a high-level p y to communicate w y to communicate w y the programmerco obligations made provide a powerful plex distributed s gh-level modeling nate the need for everyday experier in real life traf time conflict res goal unattainable	12b. DISTRIBUTION CODE programming language, in with other programs in a buld explicitly represent gram (or 'agent'), includ to them. Our hypothesis abstraction that would systems. and communication, we were explicit coordination in the the notion of social 1 fic rules restrict one solution while driving but e, so could restrictions
Approved for public r Approved for public r Agent oriented pro which a programmer is uniform, high-level 1 in the program (or 'a the beliefs about the was that such 'mental enable the analysis a In addition to suc interested in global is the place. Specifica and conventions. The enough to eliminate m not so much so as to is on computation strike directly by a system-	statement release: distribution gramming was proposed given the opportunity anguage. Furthermore gent') the relationsh other agents and the -level' design would p nd even design of comp h coordination via hig mechanisms that elimin lly, we borrowed from idea is that just as ost the need for real- make any navigational a good balance. These	unlimited. as a high-level p y to communicate w , the programmerco ip with other prog obligations made provide a powerful plex distributed s gh-level modeling nate the need for everyday experier in real life traf time conflict res goal unattainable se restrictions co	programming language, in with other programs in a buld explicitly represent gram (or 'agent'), includi to them. Our hypothesis abstraction that would systems. and communication, we wer explicit coordination in the the notion of social 1 fic rules restrict one solution while driving but e, so could restrictions buld either be imposed
Approved for public r Approved for public r Agent oriented pro which a programmer is uniform, high-level 1 in the program (or 'a the beliefs about the was that such 'mental enable the analysis a In addition to suc interested in global the place. Specifica and conventions. The enough to eliminate m not so much so as to on computation strike directly by a system- process of trial an e	statement release: distribution gramming was proposed given the opportunity anguage. Furthermore gent') the relationsh other agents and the -level' design would p nd even design of comp h coordination via hig mechanisms that elimin lly, we borrowed from idea is that just as ost the need for real- make any navigational a good balance. Thes or network-administrat	unlimited. as a high-level p y to communicate w , the programmerco obligations made provide a powerful plex distributed s gh-level modeling nate the need for everyday experier in real life traf time conflict res goal unattainable se restrictions co tor, or could emer	125. DISTRIBUTION CODE programming language, in with other programs in a puld explicitly represent gram (or 'agent'), includi to them. Our hypothesis abstraction that would systems. and communication, we wer explicit coordination in nee the notion of social 1 fic rules restrict one solution while driving but e, so could restrictions buld either be imposed rge dynamically through a
Approved for public r Approved for public r Agent oriented pro which a programmer is uniform, high-level 1 in the program (or 'a the beliefs about the was that such 'mental enable the analysis a In addition to suc interested in global is the place. Specifica and conventions. The enough to eliminate m not so much so as to r on computation strike directly by a system- process of trial an e 14. SUBJECT TERMS	statement release: distribution gramming was proposed given the opportunity anguage. Furthermore gent') the relationsh other agents and the -level' design would p nd even design of comp h coordination via hig mechanisms that elimin lly, we borrowed from idea is that just as ost the need for real- make any navigational a good balance. Thes or network-administrat rror in the population	unlimited. as a high-level p y to communicate w , the programmerco ip with other prog obligations made provide a powerful plex distributed s gh-level modeling nate the need for everyday experier in real life traf time conflict res goal unattainable se restrictions co tor, or could emer	12b. Distribution CODE programming language, in with other programs in a puld explicitly represent gram (or 'agent'), includi to them. Our hypothesis abstraction that would systems. and communication, we were explicit coordination in the the notion of social 1 fic rules restrict one solution while driving but e, so could restrictions buld either be imposed rge dynamically through a 15. NUMBER OF PAGES 3
Approved for public r Approved for public r Agent oriented pro which a programmer is uniform, high-level 1 in the program (or 'a the beliefs about the was that such 'mental enable the analysis a In addition to suc interested in global the place. Specifica and conventions. The enough to eliminate m not so much so as to r on computation strike directly by a system- process of trial an e 14. SUBJECT TERMS agent-oriented program	statement release: distribution gramming was proposed given the opportunity anguage. Furthermore, gent') the relationshi other agents and the -level' design would p nd even design of comp h coordination via hig mechanisms that elimin lly, we borrowed from idea is that just as ost the need for real- make any navigational a good balance. Thes or network-administrat rror in the population	unlimited. as a high-level p y to communicate w , the programmerco ip with other prog obligations made provide a powerful plex distributed s gh-level modeling hate the need for everyday experier in real life traf time conflict res goal unattainable se restrictions co tor, or could emer	12b. Distribution CODE programming language, in with other programs in a puld explicitly represent gram (or 'agent'), includi to them. Our hypothesis abstraction that would systems. and communication, we wer explicit coordination in the the notion of social 1 fic rules restrict one solution while driving but e, so could restrictions buld either be imposed rge dynamically through a 15. NUMBER OF PAGES 3 bordination the coost 16. PAGES COOST 17. PAGES COOST 18. PAGES COOST 18. PAGES COOST 19. PAGES COOST 10. PAGES COOST 1
Approved for public r Approved for public r Agent oriented pro which a programmer is uniform, high-level 1 in the program (or 'a the beliefs about the was that such 'mental enable the analysis a In addition to suc interested in global the place. Specifica and conventions. The enough to eliminate m not so much so as to r on computation strike directly by a system- process of trial an e 1. SECURITY CLASSIFICATION	statement release: distribution gramming was proposed given the opportunity anguage. Furthermore, gent') the relationsh other agents and the -level' design would p nd even design of comp h coordination via hig mechanisms that elimin lly, we borrowed from idea is that just as ost the need for real- make any navigational a good balance. Thes or network-administrat rror in the population mming, mental state,	unlimited. as a high-level p y to communicate w , the programmerco ip with other prog obligations made provide a powerful plex distributed s gh-level modeling hate the need for everyday experier in real life traf time conflict res goal unattainable se restrictions co tor, or could emer	12b. DISTRIBUTION CODE programming language, in with other programs in a puld explicitly represent gram (or 'agent'), includit to them. Our hypothesis abstraction that would systems. and communication, we were explicit coordination in fic rules restrict one solution while driving but e, so could restrictions puld either be imposed ordination and commically through a 11. NUMBER OF PAGES a prodination a prodination a production a bordination a bordination a bordination a bordination bordination a bordination bordination bordination bordination bordination bordination bordination bordination bordination
 Approved for public r Asstract (Maximum 200 wor Agent oriented pro which a programmer is uniform, high-level 1 in the program (or 'a the beliefs about the was that such 'mental enable the analysis a In addition to suc interested in global is the place. Specifica and conventions. The enough to eliminate m not so much so as to on computation strike directly by a system- process of trial an e SECURITY CLASSIFICATION OF REPORT unclassified 	statement release: distribution gramming was proposed given the opportunity anguage. Furthermore gent') the relationship other agents and the -level' design would p nd even design of comp h coordination via hig mechanisms that elimin lly, we borrowed from idea is that just as ost the need for real- make any navigational a good balance. These or network-administrate rror in the population mming, mental state, in 18. SECURITY CLASSIFICATION OF THIS PAGE unclassified	unlimited. as a high-level p y to communicate w , the programmerco ip with other prog obligations made provide a powerful plex distributed s gh-level modeling nate the need for everyday experier in real life traf time conflict res goal unattainable se restrictions co tor, or could emer load balancing, co	12b. DISTRIBUTION CODE Drogramming language, in with other programs in a Duld explicitly represent gram (or 'agent'), includi to them. Our hypothesis abstraction that would systems. and communication, we were explicit coordination in fic rules restrict one solution while driving but estimation and communication, we were estimation and communication, we were explicit coordination in fic rules restrict one solution while driving but estimation fic rules restrictions build either be imposed ege dynamically through a 11. NUMBER OF PAGES a bordination a bordination a bordination a a bordination a bordination a bordination bordination bordination bordination

GENERAL INSTRUCTIONS FOR COMPLETING SF 298

The Report Documentation Page (RDP) is used in announcing and cataloging reports. It is important that this information be consistent with the rest of the report, particularly the cover and title page. Instructions for filling in each block of the form follow. It is important to stay within the lines to meet optical scanning requirements.

Block 1. Agency Use Only (Leave blank).

Block 2. <u>Report Date</u>. Full publication date including day, month, and year, if available (e.g. 1 Jan 88). Must cite at least the year.

Block 3. <u>Type of Report and Dates Covered</u>. State whether report is interim, final, etc. If applicable, enter inclusive report dates (e.g. 10 Jun 87 - 30 Jun 88).

Block 4. <u>Title and Subtitle</u>. A title is taken from the part of the report that provides the most meaningful and complete information. When a report is prepared in more than one volume, repeat the primary title, add volume number, and include subtitle for the specific volume. On classified documents enter the title classification in parentheses.

Block 5. <u>Funding Numbers</u>. To include contract and grant numbers; may include program element number(s), project number(s), task number(s), and work unit number(s). Use the following labels:

- C Contract G - Grant
- PR Project
- TA Task
- PE Program Element
- WU Work Unit Accession No.

Block 6. <u>Author(s)</u>. Name(s) of person(s) responsible for writing the report, performing the research, or credited with the content of the report. If editor or compiler, this should follow the name(s).

Block 7. <u>Performing Organization Name(s) and</u> <u>Address(es)</u>. Self-explanatory.

Block 8. <u>Performing Organization Report</u> <u>Number</u>. Enter the unique alphanumeric report number(s) assigned by the organization performing the report.

Block 9. <u>Sponsoring/Monitoring Agency Name(s)</u> and Address(es). Self-explanatory.

Block 10. <u>Sponsoring/Monitoring Agency</u> . <u>Report Number</u>. (If known)

Block 11. <u>Supplementary Notes</u>. Enter information not included elsewhere such as: Prepared in cooperation with...; Trans. of...; To be published in.... When a report is revised, include a statement whether the new report supersedes or supplements the older report.

Block 12a. <u>Distribution/Availability Statement</u>. Denotes public availability or limitations. Cite any availability to the public. Enter additional limitations or special markings in all capitals (e.g. NOFORN, REL, ITAR).

- DOD See DoDD 5230.24, "Distribution Statements on Technical Documents."
- DOE See authorities.
- NASA See Handbook NHB 2200.2.
- NTIS Leave blank.

Block 12b. Distribution Code.

- DOD Leave blank.
- DOE Enter DOE distribution categories from the Standard Distribution for Unclassified Scientific and Technical Reports.
- NASA Leave blank.
- NTIS Leave blank.

Block 13. <u>Abstract</u>. Include a brief (Maximum 200 words) factual summary of the most significant information contained in the report.

B'ock 14. <u>Subject Terms</u>. Keywords or phrases entifying major subjects in the report.

Block 15. <u>Number of Pages</u>. Enter the total number of pages.

Block 16. <u>Price Code</u>. Enter appropriate price code (NTIS only).

Blocks 17. - 19. <u>Security Classifications</u>. Selfexplanatory. Enter U.S. Security Classification in accordance with U.S. Security Regulations (i.e., UNCLASSIFIED). If form contains classified information, stamp classification on the top and bottom of the page.

Block 20. <u>Limitation of Abstract</u>. This block must be completed to assign a limitation to the abstract. Enter either UL (unlimited) or SAR (same as report). An entry in this block is necessary if the abstract is to be limited. If blank, the abstract is assumed to be unlimited

Final Report on AFOSR grant AF F49620-94-1-0090: Communication and coordination in multi-agent systems: agent-oriented programming and computational social laws. Yoav Shoham Director, Robotics Laboratory

Computer Science Department Stanford University

1 Background

The premise our research has been that in emerging networked environments it will increasingly be the case that neither authority nor information are concentrated in a single locus, and software will have to be written in a way that reflects this fact. Specifically, we posited an environment in which multiple programs operate, each controlled by and embodying the wishes of different masters. These programs would require to coordinate with one another, whether to achieve tasks neither can achieve alone or to resolve conflicts around shared resources (including computational resources such as network printers and other resources such as transportation vehicles). We set out to investigate two new types of mechanism aimed at achieving such coordination.

Agent oriented programming was proposed as a high-level programming language, in which a programmer is given the opportunity to communicate with other programs in a uniform, high-level language. Furthermore, the programmer could explicitly represent in the program (or 'agent') the relationship with other program (or 'agents'), including the beliefs about the other agents and the obligations made to them. Our hypthesis was that such 'mental-level' design would provide a powerful abstraction that would enable the analysis and even design of complex distributed systems.

In addition to such coordination via high-level modeling and communication, we were interested in global mechanisms that eliminate the need for explicit coordination in the first place. Specifically, we borrowed from everyday experience the notion of social laws and conventions. The idea is that just as in real life traffic rules restrict one enough to eliminate most of the need for real-time conflict resolution while driving but not so much so as to make any navigational goal unattainable, so could restrictions on computation strike a good balance. These restrictions could either be impose directly by a system- or network-administrator, or could emerge dynamically

1

19971006 153

DITE QUALITY INSPECTS) S

through a process of trial an error in the population.

Below is a summary of our achievements on these efforts during the period of the contract. Following it are a few representative publications.

2 AOP and mental-level modeling

Our first experience was, in a sense, negative. The framework of AOP, while very attractive conceptually, proved too high-level to be useful in particular applications. While we experimented with several, including distributed transportation planning and network management, the details of the particular application ended up dominating the power of AOP itself. Our tentative conclusion from this experience that AOP is useful as a design principle, but each domain calls for specific AOP-inspired language. We are currently investigating, not under the AFOSR contract, applying these lessons to interapplication communication standards.

At the same, our experience in applying the mental state component of AOP alone met with success. Up until the time of this research, logics of knowledge (that is, logics in which one can state what is known by a oarticular agent, not only what is true or false) were applied solely to reason about distributed protocols. We were able to show that these same tools, albeit in modified form, are useful in the robotic domain. Specifically, we were able to synthesize provably optimal termination conditions for robot motion planning, and were furthermore able to present an algorithm to automatically distribute a centralized robotic controller among the different robotic components. These results are reported in two of the attached papers.

3 Computational social systems

Our results here are quite crisp, and are presented four attached papers. In the first paper we investigate the difficulty of sythesizing useful social laws by carefully analysing the domain at hand. We first perform a case study of manual construction of traffic laws in a grid system, and then investigate the computational complexity of automatically synthesizing such social laws.

In a second paper we investigate the automatic emergence of such laws (and specifically, social conventions), as a result of a stochastic process in a population. This investigation is carried out in a mathematical setting, and so in a third paper we investigate the pheneomena in a quasi-realistic load-balancing setting. Specifically, we create a setting in which n processes stochastically generate jobs, each of which must be submitted to one of m processors, where each processor has some varying and unknown capacity. We show how the processes learn to distribute the jobs optimally without any global information or other hints, based purely on their accumulated individual histories.

Finally, we apply these ideas in a truly real-world setting. In the fourth paper attached herein we report on results with an adaptive information retrieval system. The goal of this system, (called Fab) is to fetch users Web pages and over time, based on feedback, home in on the users' interests. Fab employs both content-based and collaborative components. Importantly, at the core of Fab's architecture are a set of collection agents, which must between them perform optimal search of a very large space (the Web) in service of an unknown and ever changing set of users. Fab has been operational for a couple of years now; it has proved very fertile ground in which to investigate the emergence of coordination, and is also now beginning to attract much attention due to its impressive performance and friendly design.