Project No. E-24-615
Project Director: Dr. John Bartholdi
Sponsor: National Science Foundation

Type Agreement: Grant No. ECS-8351313
Award Period: From 9/1/84 To 5/31/86
Sponsor Amount: Estimated: $25,000 Funded: $25,000

Title: Presidential Young Investigator Award (Routing and Scheduling Problems)

ADMINISTRATIVE DATA
1) Sponsor Technical Contact: Dr. Michael J. Polis
Div. of Electrical Computer and Systems Engineering
National Science Foundation
1800 "G" Street, N.W.
Washington, D.C. 20550
Phone: (202) 357-9618
Defense Priority Rating: N/A

2) Sponsor Admin/Contractual Matters: Mary Frances O'Connell
Grants Official
National Science Foundation
1800 "G" Street, N.W.
Washington, D.C. 20550
Phone: (202) 357-9602

Military Security Classification: N/A
(or) Company/Industrial Proprietary: N/A

RESTRICTIONS
See Attached NSF Supplemental Information Sheet for Additional Requirements.

Travel: Foreign travel must have prior approval — Contact OCA in each case. Domestic travel requires sponsor approval where total will exceed greater of $500 or 125% of approved proposal budget category.

Equipment: Title vests with GIT

COMMENTS:
Includes usual 6-month unfunded flexibility period.
NOTICE OF PROJECT CLOSEOUT

Closeout Notice Date 02/11/91

Project No. E-24-615
Project Director BARTHOLDI J J
Center No. R5805-0A0
School/Lab ISYE

Sponsor NATL SCIENCE FOUNDATION/GENERAL
Contract/Grant No. ECS-8351313
Contract Entity GTRC
Prime Contract No.

Title PRESIDENTIAL YOUNG INVESTIGATOR AWARD
Effective Completion Date 900228 (Performance) 900528 (Reports)

Closeout Actions Required:  

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Comments

Subproject Under Main Project No.
Continues Project No.

Distribution Required:

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NOTE: Final Patent Questionnaire sent to PDPI.
Dr. Michael Polis  
Division of Electrical, Computer, and  
Systems Engineering  
National Science Foundation  
1800 G Street, N.W.  
Washington, D.C. 20550  

RE: Grant No. ECS-8351313, Presidential Young Investigator Award  

Dear Dr. Polis,  

Enclosed is a report of my progress to date and description of my current support.  

So far I have secured the following industry funds:  

$10,000 from Pepsico Foundation  
$72,444 from IBM, Kingston, NY  
$37,500 from Litton Industries  

TOTAL: $119,944  

National Science Foundation has provided matching funds as follows:  

($37,500) first year of PYI  
($37,500) second year of PYI  
($37,500) third year of PYI  

$7,444 CURRENTLY UNMATCHED  

In addition I expect to secure another $37,500 to be matched this year, probably from Litton, or else from General Electric.  

I am grateful for the generous support of NSF.  

Sincerely,  

[Signature]  

Associate Professor
May 17, 1987

PROGRESS REPORT

National Science Foundation Grant No. ECS-8351313

Presidential Young Investigator Award

John J. Bartholdi, III
Associate Professor
School of Industrial and Systems Engineering
Georgia Institute of Technology
Atlanta, Georgia 30332
1-404-894-3036

I. Research

A. Papers published in refereed journals

When preferences are "single-peaked" - a psychological model from the theory of social choice - then a stable matching always exists, is unique, and can be constructed in O(n) time. We also show how to quickly recognize when a set of preferences is single-peaked.

The "best" control algorithm for operating a carousel conveyor depends on two measurable parameters that describe the load on the carousel. We give a spectrum of algorithms that are appropriate for specific situations. Among the more interesting results: suppose you must retrieve orders (collections of items) for customers; while the problem of doing that quickly is provably hard, a simple heuristic never requires more than 1 revolution of the carousel beyond optimal...independently of the number of customer orders to be retrieved! Equally surprisingly, a greedy heuristic never requires more carousel revolutions than log(# storage locations), again independently of the number of customer orders.

B. Papers accepted by refereed journals

Many warehouses sequence retrievals by simply sorting according to bin number of the storage locations. We show how to design the most effective bin-numbering scheme. Considered geometrically, the problem is to design the best (discretized) spacefilling curve that visits the points in question and takes into account their probabilities of being in a random order. Our algorithm is novel in that it can design the best bin-numbering scheme based on sample data - it does not depend on artificial assumptions such as independence.

Tail probabilities are crucial to system design since they represent the probability that the system exhibits extremes of performance. Unfortunately, it is difficult to compute such probabilities. This paper explains why by showing that even simple versions of the problem are #P-hard.

Problems that are #P-hard are thought to be much harder than NP-hard, and indeed, not even a fast heuristic with guaranteed accuracy is known for any #P-hard problem. However, we give a simple heuristic with the following novel property: it computes the approximate tail probability to a problem that approximates the original. Moreover, the tolerable error may be specified in advance of the computation. Remarkably, the effort to compute the tail probability to within the specified error grows only "almost linearly" in the reciprocal of the error.

C. Papers submitted to refereed journals

J. Bartholdi, C. Tovey, and M. Trick, "The computational difficulty of manipulating an election", submitted to *Social Choice and Welfare*.

We show how computational complexity might help protect the integrity of social choice. We exhibit a voting scheme that is computationally resistant to manipulation. Specifically, the scheme identifies winners in polynomial time, but it is NP-complete to decide how to exploit knowledge of the preferences of other voters. We also give an algorithm to manipulate many standard voting schemes in polynomial time.

J. Bartholdi, C. Tovey, and M. Trick, "A historical voting scheme for which it can be difficult to tell who won the election", submitted to *American Mathematical Monthly*.

A voting scheme suggested by Lewis Carroll is capable of behavior that is novel in the history of practical voting: it is NP-hard to tell whether any particular candidate has won the election! Carroll would have enjoyed the idea that a candidate's mandate might have expired before it was recognized.


We show how to use spacefilling curves to succinctly but accurately summarize the information about geometrical problems; this allows fast heuristics since there is less information to be manipulated. In addition to giving very general theoretical performance analysis, we discuss such immediate practical applications as schemes for controlling naval gunfire, for assigning zipcodes, and for numbering storage locations in a warehouse.


A heavily revised version of an earlier draft, with additional results. The spacefilling curve heuristic seems to be the best of the fast TSP heuristics. In addition to all of its other nice properties, it also tends to minimize the length of the longest edge in the tour, thereby giving solutions that are good simultaneously to TWO problems: the minsum TSP (arbitrary metric!), and the minmax TSP.

C. Work in progress

J. Bartholdi and L. Platzman, "Decentralized control of a fixed route, automated
J. Bartholdi and J. Zhang, "Partitioning heuristics for multi-dimensional packing".

D. Students supported on grant funds

Michael A. Trick; Ph.D. student supported on funds from the Production and Distribution Research Center, of which I am a co-principal investigator. Trick is now graduating. He has won second place in the Nicholson Student Paper Contest sponsored by ORSA; a 1 year postdoctorate at the Institute for Mathematics and Its Applications at the University of Minnesota; a postdoctorate from the National Research Council.

Zhang Jixian, Ph.D. student supported on funds from the Production and Distribution Research Center. Zhang has won a 6 month postdoctorate at the Institute for Mathematics and Its Applications at the University of Minnesota. He will graduate in about 6 months.

Li Junsheng, Ph.D. student supported on NSF funds. Li has now finished all course work and Ph.D. comprehensive exams, and has begun writing his thesis.

Wang Lim; Ph.D. student supported on NSF funds. Lim is finishing a thesis on decentralized control of automatic guided vehicle systems.

E. Sponsored research activity

Principal investigator, Presidential Young Investigator Award, National Science Foundation (2 months support during the summer).

Funds to date from industry for the PYI program:

- $10,000 from PepsiCo Foundation
- $72,444 from IBM, Kingston, NY
- $37,500 from Litton Industries

(These funds will provide 1 month additional support during the summer)

Co-principal investigator, Production and Distribution Research Center, funded by the Office of Naval Research (25% support during the academic year).
April 11, 1988

RE: Grant No. ECS-8351313, Presidential Young Investigator Award

Dear Dr. Polis,

Enclosed is a report of my progress to date and description of my current support. I am especially proud of the three papers on voting (with C. Tovey and M. Trick), which, I am told, make a fundamental contribution to the field.

So far I have secured the following industry funds:

- $10,000 from Pepsico Foundation
- $72,444 from IBM, Kingston, NY
- $37,500 from Litton Industries
- $37,500 from Litton Industries

TOTAL: $157,444

National Science Foundation has provided matching funds as follows:

- ($37,500) first year of PYI
- ($37,500) second year of PYI
- ($37,500) third year of PYI
- ($37,500) fourth year of PYI

UNMATCHED: $7,444

In addition I expect to secure another $37,500 to be matched this year, probably from Litton.

I am grateful for the generous support of NSF.

Sincerely,

John J. Bartholdi, III
Associate Professor
I. Research

A. Papers published in refereed journals


We show how to use spacefilling curves to succinctly but accurately summarize the information about geometrical problems; this allows fast heuristics since there is less information to be manipulated. In addition to giving very general theoretical performance analysis, we discuss such immediate practical applications ranging from controlling naval gunfire to assigning zipcodes.


We show how to design the numbering of bins in a warehouse so that retrieving items according to their bin number produces short retrieval routes.

B. Papers accepted by refereed journals


A very simple control algorithm enables a fleet of unit-load AGV's to quickly deliver items to their destinations. The algorithm is highly decentralized, requires minimal information, and is provably good, even for the dynamic case in which items continue to arrive into the system while others are being delivered.

A major manufacturer built a commercial AGV system to these specifications based on an early draft of this paper.


It is important for design engineers to compute accurate tail probabilities because they represent the chance of extreme system behavior. Unfortunately, it is provably difficult ($\#P$-hard) to compute general tail probabilities. In fact, no one has ever found even a provably good heuristic for this, or indeed for any problem that is $\#P$-hard. We provide a fast heuristic with this unusual property: the user stipulates the desired
accuracy of the model problem and the desired accuracy of the solution; the heuristic returns an approximate answer to the approximate problem!


We show how computational complexity might help protect the integrity of social choice. We exhibit a voting scheme that is computationally resistant to manipulation. Specifically, the scheme identifies winners in polynomial time, but it is NP-complete to decide how to exploit knowledge of the preferences of other voters. We also give an algorithm to manipulate many standard voting schemes in polynomial time.

J. Bartholdi, C. Tovey, and M. Trick (1988). "Voting schemes for which it can be difficult to tell who won the election", to appear in Social Choice and Welfare.

A voting scheme suggested by Lewis Carroll is capable of behavior that is novel in the history of practical voting: it is NP-hard to tell whether any particular candidate has won the election! Carroll would have enjoyed the idea that a candidate's mandate might have expired before it was recognized.

We also introduce an "impracticality theorem", that says roughly that any voting scheme that does enough work to satisfy certain simple fairness criteria must do so much work that it is NP-hard to tell who won the election!


The spacefilling curve heuristic seems to be the best of the fast TSP heuristics. In addition to all of its other nice properties, it also tends to minimize the length of the longest edge in the tour, thereby giving solutions that are good simultaneously to TWO problems: the minsum TSP (arbitrary metric!), and the minmax TSP.

C. Papers submitted to refereed journals


We show that a very simple on-line heuristic for 2-dimensional packing can have expected performance that rivals those of off-line heuristics.

J. Bartholdi, C. Tovey, and M. Trick (1988). "How hard is it to cheat in an election?", submitted to Econometrica.

We show how voting schemes can be classified based on their susceptibility to different types of manipulation. Along the way we show how to dodge Arrow's famous impossibility theorem on computational grounds: plurality voting satisfies all of Arrow's hypotheses except one; and to recognize an instance of failure of the remaining hypothesis is provably difficult!

C. Work in progress

J. Bartholdi and J. Li (1988). "The design and implementation of an interactive program for balancing assembly lines".

J. Bartholdi and J. Li (1988). "Scheduling cranes along a line to make printed circuit boards".

J. Bartholdi (1988). "Scheduling interviews at a job fair".
J. Bartholdi, J. Vande Vate, and J. Zhang (1988). "Balanced packing".

D. Students supported on grant funds

Michael A. Trick; Ph.D. student supported on funds from the Production and Distribution Research Center, of which I am a co-principal investigator. Trick has just graduated. He won second place in the Nicholson Student Paper Contest sponsored by ORSA; a 1 year postdoctorate at the Institute for Mathematics and Its Applications at the University of Minnesota; a postdoctorate from the National Research Council; and a postdoctorate from the National Science Foundation. After his postdoctorates he will join the faculty of Carnegie-Mellon University.

Zhang Jixian, Ph.D. student supported on funds from the Production and Distribution Research Center. Zhang has won a 6 month postdoctorate at the Institute for Mathematics and Its Applications at the University of Minnesota. He will graduate at the end of August 1988.

Li Junsheng, Ph.D. student supported on NSF funds. Li has now finished all course work and Ph.D. comprehensive exams, and is writing his thesis on material handling in a flow shop.

Wang Lim; Ph.D. student supported on NSF funds. Lim is finishing a thesis on decentralized control of automatic guided vehicle systems.

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$37,500 from Litton Industries
$37,500 from Litton Industries

(these funds will provide 1 month additional support during the summer)

Co-principal investigator, Production and Distribution Research Center, funded by the Office of Naval Research (25% support during the academic year).
The data requested below will be used to develop a statistical profile on the personnel supported through NSF grants. The information on this part is solicited under the authority of the National Science Foundation Act of 1950, as amended. All information provided will be treated as confidential and will be safeguarded in accordance with the provisions of the Privacy Act of 1974. NSF requires that a single copy of this part be submitted with each Final Project Report (NSF Form 98A); however, submission of the requested information is not mandatory and is not a precondition of future awards. If you do not wish to submit this information, please check this box.

Please enter the numbers of individuals supported under this NSF grant. Do not enter information for individuals working less than 40 hours in any calendar year.

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Number of individuals who have a handicap that limits a major life activity.

*Use the category that best describes person's ethnic/racial status. (If more than one category applies, use the one category that most closely reflects the person's recognition in the community.)

AMERICAN INDIAN OR ALASKAN NATIVE: A person having origins in any of the original peoples of North America, and who maintains cultural identification through tribal affiliation or community recognition.

ASIAN OR PACIFIC ISLANDER: A person having origins in any of the original peoples of the Far East, Southeast Asia, the Indian subcontinent, or the Pacific Islands. This area includes, for example, China, India, Japan, Korea, the Philippine Islands, and Samoa.

BLACK, NOT OF HISPANIC ORIGIN: A person having origins in any of the black racial groups of Africa.

HISPANIC: A person of Mexican, Puerto Rican, Cuban, Central or South American or other Spanish culture or origin, regardless of race.

WHITE, NOT OF HISPANIC ORIGIN: A person having origins in any of the original peoples of Europe, North Africa or the Middle East.

THIS PART WILL BE PHYSICALLY SEPARATED FROM THE FINAL PROJECT REPORT AND USED AS A COMPUTER SOURCE DOCUMENT. DO NOT DUPLICATE IT ON THE REVERSE OF ANY OTHER PART OF THE FINAL REPORT.
PART I—PROJECT IDENTIFICATION INFORMATION

1. Institution and Address
   Ga Tech Research Corp
   Industrial & Systems Engineering
   Atlanta, GA 30332

2. NSF Program
   Presidential Young Investigator

3. NSF Award Number
   ECS-835133

4. Award Period
   From 9/1/84 To 2/28/90

5. Cumulative Award Amount
   $312,500

6. Project Title
   Algorithm for Logistics and Coordination

PART II—SUMMARY OF COMPLETED PROJECT (FOR PUBLIC USE)

(See enclosed report)

PART III—TECHNICAL INFORMATION (FOR PROGRAM MANAGEMENT USES)

1. ITEM (Check appropriate blocks)
   a. Abstracts of Theses
   b. Publication Citations
   c. Data on Scientific Collaborators
   d. Information on Inventions
   e. Technical Description of Project and Results
   f. Other (specify)

2. Principal Investigator/Project Director Name (Typed)
   John J. Bartholdi, III

3. Principal Investigator/Project Director Signature

4. Date

Form Approved OMB No 3145-00
To Whom It May Concern,

This is to submit a report of accomplishments for my last year of funding under Presidential Investigator Award and Grant ECS-8351313.

The published papers reflect my continuing interest in algorithms for logistics and coordination. The following recent publications gratefully acknowledge NSF support.

- Bartholdi, J. J. III, C. A. Tovey, and M. A. Trick (1989). "Voting schemes for which it can be difficult to tell who won the election", *Social Choice and Welfare* 6:157–165.

Recent invited presentations include the following.

• "Economics of forager allocation in a honeybee colony", presented at North Carolina State University 1990
  Ohio State University, April 1990
  The Center for Political Economy, Washington University at St. Louis, March 1990
  Graduate School of Industrial Administration, Carnegie-Mellon University, February 1990
• "Computational issues in social choice", University of Waterloo, Waterloo, Canada, October 1989.
• "The computational difficulty of manipulating an election", Table ronde sur modélization, analyse, et agrégation des préférences et des choix, Centre des Rencontres Mathematiques International, Marseille, April 1988.

I have recently organized and chaired the following sessions at national conferences (and delivered talks therein).

Applied Combinatorial Optimization, ORSA/TIMS¹ Philadelphia, October 1990
Computational issues in social choice, ORSA/TIMS Las Vegas, May 1990
Applications of Integer Programming, ORSA/TIMS New York, October 1990
Packing, ORSA/TIMS Vancouver, May 1989

Recent Ph. D. students include the following.

**W. Nulty** Expected graduation: 1993

¹Joint National Meeting of the Operations Research Society of America and The Institute of Management Sciences

2
D. Eisenstein Expected graduation: 1992
S. Amiouny Expected graduation: 1992
K. McCroan Expected graduation: 1991

A. Ramudhin, 1990 Université de Trois Rivieres, Quebec; thesis: "Two-stage manufacturing processes".


W. Lim, 1988 Deputy General Manager for Research and Development, Daewoo Telecom; thesis: "Control algorithms for unit-load automatic guided vehicles"

Finally, I am very grateful for the generous support of NSF during the five years of this award.

Sincerely,

John J. Bartholdi, III
Associate Professor