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NONLINEAR ANALYSIS, SCIENTIFIC COMPUTATION, AND CONTINUUM MECHANICS APPLIED TO THE SCIENCE OF MATERIALS

CENTER FOR NONLINEAR ANALYSIS
Final Report

Principal Investigators: Morton E. Gurtin
William O. Williams

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13. ABSTRACT *(Maximum 200 words)*

This grant enabled the department to form the Research Group in Mathematical Materials Science in 1990, a group that formed the nucleus of the Center for Nonlinear Analysis, established in 1991, by the ARO. The Center has created a vigorous environment for collaboration among mathematicians and allied scientists. Within the international mathematics community the Center has assumed a leadership role, especially for questions related to materials science. The major research effort has focused toward developing, analyzing, and unifying mathematical models that characterize material behavior at a phenomenological level. The main thrust is applied nonlinear analysis, nonlinear continuum physics, and scientific computation. The educational goals have been to train young scientists, and to train and involve female and minority students in the sciences.

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NONLINEAR ANALYSIS, SCIENTIFIC COMPUTATION, AND CONTINUUM MECHANICS APPLIED TO THE SCIENCE OF MATERIALS

Army Research Office

Principle Investigators: M. E. Gurtin, W. O. Williams

Department of Mathematics, Carnegie Mellon University

1. SUMMARY

This grant enabled the department to form the Research Group in Mathematical Materials Science in 1990, a group that formed the nucleus of the Center for Nonlinear Analysis, established in 1991 by the ARO. The Center has created a vigorous environment for collaboration among mathematicians and allied scientists. Within the international mathematics community the Center has assumed a leadership role, especially for questions related to materials science. The major research effort has focused toward developing, analyzing, and unifying mathematical models that characterize material behavior at a phenomenological level. The main thrust is applied nonlinear analysis, nonlinear continuum physics, and scientific computation. The educational goals have been to train young scientists, and to train and involve female and minority students in the sciences. Highlights include five major conferences, seven research workshops (highly focused workshops bringing together small groups of varied backgrounds to identify and attack major outstanding problems), and a four-week Undergraduate Mathematics Institute targeted at minorities and women. The training of 4-5 p ostdocs and 7-8 graduate students each year has been a major activity. The Center has attracted scores of visitors, both nationwide and international. Three interdisciplinary courses were introduced, as was a program of interdisciplinary weekly seminars in nonlinear analysis. A major outcome has been the initiation of several cross-disciplinary collaborations. Much of the work developed in conjunction with the Center has: (I) led to a physically consistent framework that seems useful to applied scientists for the development of specific theories; (ii) led to physically well-motivated models that are studied by analysts; (iii) led to new techniques of analysis used by other mathematicians.

2. SPECIFIC ACTIVITIES

A. Major conferences and workshops: *Calculus of Variations and Nonlinear Material Behavior:* C. Dafermos (Brown U.), J. L. Ericksen (U. Minnesota), I. Fonseca (CMU), R. James (U. Minnesota), D. Kinderlehrer (CMU), B. McLeod (U. Pittsburgh), V. J. Mizel (CMU), W. Mullins (CMU). *Motion by Mean Curvature and the Evolution of Phase Boundaries:* F. Almgren (Princeton U.), G. Caginalp (U. Pittsburgh), G. b. McFadden (NIST), R. Sekerka (CMU), H. M. Soner (CMU), E. Souganidies (Brown U.), P. Voorhees (Northwestern U.). *Perspectives in Analysis:* W. Fleming (Brown U.), A. Friedman (U. Minnesota), J. Glimm (State U. N.Y. Stony Brook), R. Glowinski (U. Houston), D. Kinderlehrer (CMU), J. L. Lions, (College de France), P. L. Lions (U. Paris-Dauphine), A. Majda (Princeton U.), W. Mullins (CMU), G. Sell (U. Minnesota),

J. F. Kalthoff (Ruhr U. Bochum), R. Malek-Madani (U.S. Naval Academy), M. A. Meyers (U. California), W. E. Olmstead (Northwestern U.), A. Tzavaras (U. Wisconsin), J. Walter (U. S. Army Ballistic Research Laboratory), T. Wright (U.S. Army Ballistic Research Laboratory). *Computational Methods in Materials Science:* R. F. Almgren (Princeton U.), I. Babuska (U. Maryland), J. Chapman (Standard U.), C. Collins (U. Michigan), J. Dougherty (Penn State U.), Q. Du (U. Chicago), D. Fredkin (U. California), R. Guenette (Ecole Polytech. Montreal), M. Gunzburger, (Virginia Tech.), M. Luskin (U. Minnesota), L. Ma (CMU), L. Tartar (CMU), P. Voorhees (Northwestern U.), N. Walkington (CMU), Weinan E (Institute for Advanced Study), C. Gartland (Kent State U.), R. B. Griffiths (CMU), U. Hornung (SCHI), B. A. Shoykhet (Lord Corp.), E. Socolovsky (Hampton U.). *Viscoelasticity:* D. Own (CMU), B. D. Coleman (Rutgers U.), J. U. Kim (Virginia Polytechnic Institute), A. C. Pipkin (Brown U.), L. E. Fraenkel (U. of Bath), M. Heard (U. Illinois), M. Renardy (Virginia Polytechnic Institute), G. Berry (CMU), G. Del Piero (U. Ferrara), J. Nohel (U. Wisconsin), L. Wahlbin (Cornell U.), D. French (U. Cincinnati), B. Plohr (SUNY), Tai-Ping Liu (Stanford U.), H. Engler (Goergetown U.), Stig-Olof Londen (Helsinki Institute of Technology), William Hrusa (CMU).

B. **Research Workshops:** *Evolving Phase Boundaries:* M. E. Gurtin (CMU), T. Ilmanen (U. California), S. Koike (MSRI), H. M. Soner (CMU), P. E. Souganidis (Brown U.). *Whiskered Microstructures:* M. Debe (3M), T. Einstein (U. Maryland), A. Pohorille (U. California & NASA Ames), F. Rosenberger (U. Alabama), M. G. Worster, (Northwestern U.). *Highly Non-equilibrium Dynamics of Interfaces:* J. Agren, (Royal Institute of Technology), M. Aziz (Harvard U.), W. Boettinger (NIST), M. E. Gurtin (CMU). *Nonlinear Problems with Critical Growth:* S. Alama (CMU), F. Pacella (U. Rome), G. Tarantello (CMU), Y. Li (Rutgers U.). *Calculus of Variations:* L. Boccardo (Rome I.), B. Dacarogna (Lausanne), C. Evans (U. California), W. Gangbo (CMU), T. Iwaniec (Syracuse U.), S. Luckhaus (U. Bonn), A. Lutoborski, (Syracuse U.), J. Manfredi (U. Pitt, M. Slemrod (U. Wisconsin). *Convergence and the Skorohod Problem in Optimal Control:* M. Chiarolla, (U. British Columbia), P. Dupuis (Brown U.), U. Haussmann (U. British Columbia), J. Lehoczky, (CMU), L. Martins (CMU), M. Soner (CMU), L. Wein (MIT).

3. PARTICIPATING SCIENTIFIC PERSONNEL:

A. **Graduate Students:** Nenad Antonic (Ph.D., May 1992), Ana Barroso, Dan Burkett (Ph.D., August 1993), Chih-Wen Cheng (Ph.D., May 1993), Sophia Demoulini (Ph.D., May 1993), Jose Matias (Ph.D., May 1993), Dmitry Pugachevsky, Allan Struthers (Ph.D., May 1991), Stephen Watson, Gregor Weiske.

B. **Postdoctoral Fellows:** Stanley Alama, Lia Bronsard, Eliot Fried, Markos Katsoulakis, Pablo Pedregal, Piotr Rybka, Pieter Swart, Wilfrid Gangbo, Luiz Felipe Martins, Robert Peszek, Alessandro Tiero.

C. **Visitors:** R. Almgren (U. Chicago), M. Avellaneda (Courant), I. Babuska (U. Maryland), J. Ball (Heriot-Watt U.), H. Berestycki (U. Paris), M. Bertsch

(U. Bhattacharya (Courant), J. Blue (NIST), L. Boccardo (U. Rome), F. Brezzi (U. Pavia), O. Bruno (Georgia Tech), P. Cannarsa (U. Rome), G. Capriz (CNUCE), G. Carrier (Harvard), P. Cermelli (U. Torino), J. Chapman (Stanford), M. Chiarolla (Bari), M. Chipot (U. Metz), C. Collins (U. Michigan), B. Dacorogna (Ecole Polytech. Lausanne), C. Dafermos (Brown), A. De Simone (U. Rome), M. Debe (3M), G. Del Piero (U. Ferrara), J. Dougherty (Penn State), Q. Du (Michigan State), P. Dupuis (Brown), W. E (Inst. Advanced Study), T. Einstein (U. Maryland), J. Ericksen (U. of Minnesota), M. Esteban (U. Pierre et Marie Curie), C. Evans (U. California), W. Fleming (Brown), D. Fredkin (U. California), A. Friedman (U. Minnesota), C. Gartland (Kent State), P. Gerard (U. Paris Sud), Y. Giga (Hokkaido U.), R. Glowinski (U. Houston), R. Guenette (Ecole Polytech., Montreal), M. Gunzburger (Virginia Tech), J. Hale (Georgia Tech), U. Haussmann, (U. British Columbia), R. Hardt (Rice), U. Hornung (SCHI), R. Hyland (ALCOA), T. Ilmanen (Inst. Advanced Study), T. Iwaniec (Syracuse U.), R. James (U. Minnesota), S. Koike (MSRI Berkeley, CA), T. Kurtz (U. Wisconsin), P. Lax (Cournat), P. Leo (U. Minnesota), J.L. Lions (College de France), P. L. Lions (U. Paris), S. Luckhaus (U. Bonn), M. Luskin (U. Minnesota), A. Lutoborski (Syracuse U.), L. Magalhaes (I. Superior Tecnico, Portugal), A. Majda (Princeton), M. Marcus (Technion, Israel), L. Mascarenhas (Centro Mat., Lisbon), G. B. McFadden (NIST), Bryce McLeod (U. Pittsburgh), S. Muller (U. Bonn), F. Pacella (U. Rome), G. Parry (U. Bath), R. Pego (U. Maryland), B. Perthame (U. Ordeans), P. Podio-Guidugli (U. Rome), Andrew Pohorille (U. California), G. Rein (U. Munich), Fr. Rosenberger (U. Alabama), B. Rogers (Virginia Tech), D. Ross (Kodak), J. Sanchez (U. Texas), G. Sell (U. Minnesota), S. Sellers (U. Berlin), B. A. Shoykhet (Lord Corp.), M. Slemrod (U. Wisconsin), P. Souganidis (Brown), P. Sternberg (Indiana U.), B. Stoth (U. Bonn), J. Strain (Princeton), E. Tadmor (Tel-Avia U.), D. Tataru (U. Virginia), B. Temple (U. Michigan), F. Tomarelli (Politecnico Milano), G. Vergara Caffarelli (U. Rome), A. Visintin (Trento), V. Volpert (USSR Acad. Sciences), P. Voorhes (Northwestern), W. Wendland (U. Stuttgart), L. Wein (MIT), J. Willems (U. Groningen), G. Wolansky (Technion, Israel), M. Grae Worster (Northwestern), G. Zanzotto (U. Padova).

4. EDUCATIONAL EFFORTS:

A. **Workshops for undergraduate students from Historically Black Colleges and Universities:** at hampton University, November 1991, with minicourses by W. Hrusa (Calculus of Variations), M. Soner (Evolving Curves); for the Consortium of HCBU's in Atlanta, October 1972, with a minicourse by W. Hrusa (Calculus of Variations). Both workshops included a panel discussion on preparing for the succeeding in graduate school.

B. **Summer Undergraduate Mathematics Institute:** This is a four-week program for students who have completed their junior year, with participation by women and minorities especially sought. The primary goal is to prepare students for and interest them in graduate work in applied mathematics. Six students were accepted for the inaugural program held during June 1992. The core of the program was two courses, one in real analysis and the other in numerical solutions of differential equations. Each course had one hour of lecture per day, and a two-hour, problem-working session once per week. In addition, there was a computer laboratory in which students learned to use the symbolic programming language Maple. Carnegie Mellon credit was awarded for successful completion of these

courses. In conjunction with the courses there was a regular series of seminars in which faculty presented applied mathematics research topics.

C. **Nonlinear analysis seminar:** A program of weekly seminars in nonlinear analysis with strong focus on applications.

D. **Interdisciplinary courses:** Evolution of Phase Boundaries, Calculus of Variations, Homogenization and Optimal Design, Stochastic Differential Equations, Introduction to Continuum Mechanics, Advanced Topics in Analysis, Min/Max Methods, Advanced Topics in Partial Differential Equations, Deformations of Fractured Continua, Advanced Topics in Harmonic Analysis, Interpolation Spaces and Singular Integrals.

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92-NA-033 Workshop on Computational Methods in Materials Science (Abstracts), September 16-18, 1992.

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92-SA-001 S. E. Shreve and H. M. Soner, Optimal investment and consumption with transaction costs, *Math. Fin.* Submitted.