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FIVE REQUIREMENTS FOR AN APPROXIMATE NONLINEAR RESPONSE THEORY

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ABSTRACT

Five requirements are proposed which should be satisfied by any formalism attempting to calculate approximately a nonlinear response solely from a knowledge of the external field and the equilibrium fluctuations of the degree of freedom of interest. One possible approximate nonlinear response theory is then derived and discussed; it satisfies four of the five requirements while a fifth cannot be checked.

Linear response theory [1-7] was derived many years ago and is today a standard tool used in many parts of physics. The nonlinear generalization [6,8,9] is complex and not very useful, however. The problem is that, in the expansion of the response in terms of the external field E, the coefficients cannot be expressed in terms of equilibrium fluctuations of the degree of freedom, Q, that couples to the field [10]. The best one can hope for is an approximate theory that estimates the nonlinear response from equilibrium fluctuations. There is another problem which must be faced. In a non-infinitesimal field the dissipated heat cannot be ignored and the response depends on the way this heat is removed. A general formalism that estimates the response from equilibrium fluctuations does not take this into account and should be applied only at fields small enough to ensure that the temperature is almost constant throughout the sample. In many cases this condition is fulfilled for sufficiently small samples. Note that some important nonlinear phenomena actually do take place at a very small dissipation rate. An example is the flow of a polymeric liquid. It is an empirical fact [11,12] that this flow becomes nonlinear at a shear rate of order τ_M^{-1} where τ_M is the (linear) Maxwell relaxation time. Thus, if G_∞ denotes the infinite frequency shear modulus and η is the linear viscosity, the dissipation rate per unit volume is of the order G_∞^2/η at the onset of nonlinearity. For large viscosity this quantity is very small and the temperature is almost constant throughout even a relatively large sample.

In this paper five requirements are proposed which an approximate nonlinear response theory should reasonably satisfy.

Then a maximum entropy based response theory is briefly discussed, followed by the development of a more general formalism. To avoid the complications of quantum mechanics, the underlying dynamics is assumed to be classical throughout. For simplicity, it is also assumed that Q does not change sign under time-reversal.

An approximate nonlinear response theory should, by the above definition, (1), calculate the response solely from a knowledge of the external field and of the equilibrium fluctuations of $Q(t)$. The theory should, (2), satisfy causality and, (3), reflect the time-reversal invariance of the underlying equation of motion. Points (2) and (3) ensure any approximate nonlinear response theory is an extension of linear response theory. As shown by Bochkov and Kuzovlev [13,14], time-reversal invariance is conveniently expressed in terms of the "path probability" $P_{E(\tau)}[\dot{Q}(t)]$ (the probability of a $\dot{Q}(t)$-fluctuation in the external field $E(\tau)$), as

$$\frac{P_{E(\tau)}[\dot{Q}(t)]}{P_{E(-\tau)}[-\dot{Q}(-t)]} = \exp\left\{\beta \int_{-\infty}^{\infty} E(t)\,\dot{Q}(t)\,dt\right\} \tag{1}$$

where β is the inverse temperature. Equation (1) is derived by assuming thermal equilibrium at $t=-\infty$ followed by a decoupling of the heat bath and subsequent evolution in time according to the canonical equations of motion for the system interacting with the external field. The requirements (1)-(3) are sine qua non for any approximate nonlinear response theory, but there are further requirements which such a theory should reasonably satisfy. In statistical mechanics the occurrence of nonlinearities always correlates to the existence of non-Gaussian equilibrium fluctuations. For instance, a magnetic system has a field-independent susceptibility if and only if the magnetization fluctuations in equilibrium are Gaussian. In analogy to statistical mechanics it is reasonable to require that, (4), any approximate nonlinear response theory should predict an exactly linear response whenever the equilibrium Q(t)-fluctuations are Gaussian. Finally, there is a requirement which is valid also for linear response theory, (5): If Q_1 and Q_2 fluctuate independently in equilibrium, their response should be uncorrelated. Thus, if Q_1 and Q_2 are coupled to two different fields, the field E_1 should not influence the Q_2-response and vice versa. The case when the same field couples to Q_1 and Q_2 is important. Then requirement (5) ensures consistency for the response of a bulk degree of freedom, Q , since Q may be written $Q=Q_1+Q_2$ where Q_1 and Q_2 refer to different volumes of the system and therefore fluctuate independently.

The simplest solution of Eq. (1) is the "maximum entropy ansatz" [15]

$$P_{E(\tau)}\left[\dot{Q}(t)\right] = N^{-1}\, P_0\left[\dot{Q}(t)\right] \exp\left\{\beta/2 \int_{-\infty}^{\infty} E(t)\,\dot{Q}(t)\,dt\right\} \quad (2)$$

where $P_0[\dot{Q}(t)]$ is the equilibrium path probability and N is a normalization constant. Equation (2) obviously violates causality. Therefore Eq. (2) makes sense only for constant fields. In this case the response is given by [15]

$$\langle \dot{Q} \rangle_E = \sum_{n=1}^{\infty} \frac{1}{n!} \left(\frac{\beta E}{2}\right)^n \int_{-\infty}^{\infty} dt_1 \cdots dt_n \left\langle \dot{Q}(0), \dot{Q}(t_1), \cdots, \dot{Q}(t_n) \right\rangle_0 \quad (3)$$

where the sharp brackets on the right hand side denote equilibrium cumulant averages. An equivalent of Eq. (3) was first derived by Stratonovich for stochastic systems [16]. In this case Eq. (3) results from the assumption that the energy maximum to be overcome in a transition between two minima is placed midway between the two minima (in the direction of Q). To check the five requirements against Eq. (3), we note that requirements (1) and (3) are satisfied, while (2) is not. Requirement (4) is also satisfied since a system is Gaussian whenever all higher that second order cumulant averages are zero. It is easy to show that the generalization of Eq. (3) to N external fields is

$$\langle \dot{Q}_i \rangle_{\{E_j\}} = \sum_{n=1}^{\infty} \frac{1}{n!} \left(\frac{\beta}{2}\right)^n \sum_{i_1,\cdots,i_n} E_{i_1} \cdots E_{i_n} \times \int_{-\infty}^{\infty} dt_1 \cdots dt_n \, \langle \dot{Q}_i(0), \dot{Q}_{i_1}(t_1), \cdots, \dot{Q}_{i_n}(t_n) \rangle_0 \, . \tag{4}$$

From this it follows that if, e. g. , the Q_1 and Q_2 equilibrium fluctuations are uncorrelated, there is no coupling from the field E_1 to Q_2 . Thus, Eq. (3) satisfies all 5 requirements for a nonlinear response theory except causality. Note that, despite violating causality, Eq. (3) for time-independent external fields <u>is</u> an extension of linear response theory. It should also be noted that Eq. (2) for constant fields does have non-trivial applications, e. g. , to the calculation of excess current noise in random walk models where Eq. (2) leads to the correct expression [15,17].

We now turn to the problem of deriving an approximate nonlinear response theory applicable to the case with a time-dependent external field. This is achieved by approximating the exact density matrix by an expression referring to the equilibrium dynamics. For simplicity, we consider first the case of only one external field $E(t)$. The Hamiltonian is $H(t)=H_o-E(t)Q$. Suppose that, for a system initially in thermal equilibrium, the field is turned on at $t=0$. For $t>0$ the "internal energy" $H_o(t)$ is determined from the Poisson bracket expression

$$\frac{dH_o}{dt} = \{H, H_o\}$$
$$= -E(t)\{Q,H_o\} = E(t)\{H,Q\} = E(t)\,\dot{Q}\,. \tag{5}$$

If $X(0)$ and $X(t)$ denote, respectively, the starting and ending point of a path in phase space, an integration of Eq. (5) leads to

$$H_o(X(t)) - H_o(X(0)) = \int_0^t E(\tau)\,\dot{Q}(X(\tau))\,d\tau\,. \tag{6}$$

Equation (6) just expresses the fact that the change in internal energy is equal to the work performed by the external field. Now the Liouville equation for the density matrix ρ, $\frac{d\rho}{dt}=0$, implies $\rho(X(t))=\rho(X(0))$. Initially, the density matrix is $\rho(X(0))=\exp[-\beta H_o(X(0))+\beta F_o]$ where F_o is the equilibrium free energy. Thus, from Eq. (6) we get

$$\rho(X(t)) = \exp\left[-\beta H_o(X(t)) + \beta\int_0^t E(\tau)\,\dot{Q}(X(\tau))\,d\tau + \beta F_o\right]. \tag{7}$$

Define now the functional $Z_\varepsilon[E(\tau)]$ by

$$Z_\varepsilon\left[E(\tau)\right] = \mathrm{Tr}_{cl,X(t)}\ \exp\left[-\beta H_0(X(t)) + +\beta\int_0^{t+\varepsilon} E(\tau)\,\dot{Q}(X(\tau))\,d\tau + \beta F_0\right] \tag{8}$$

where $\mathrm{Tr}_{cl,X(t)}$ denotes the classical trace, i. e. , an integration over all phase space points X(t) . We obviously have

$$\langle \dot{Q}(t)\rangle_{E(\tau)} = \beta^{-1} \lim_{\varepsilon\to 0} \frac{\delta}{\delta E(t)} \ln Z_\varepsilon\left[E(\tau)\right] . \tag{9}$$

This result is exact. To arrive at an approximation that allows a calculation of the response in terms of equilibrium averages, we replace the exact path in phase space from X(0) to X(t) by the unperturbed path that ends in X(t) . Then Eq. (8) reduces to an equilibrium average:

$$Z_\varepsilon\left[E(\tau)\right] = \left\langle e^{\beta\int_0^{t+\varepsilon} E(\tau)\dot{Q}(\tau)\,d\tau}\right\rangle_0$$

$$= \exp\left[\sum_{n=2}^{\infty} \frac{\beta^n}{n!}\int_0^{t+\varepsilon} dt_1\cdots dt_n\, E(t_1)\cdots E(t_n)\langle \dot{Q}(t_1),\cdots,\dot{Q}(t_n)\rangle_0\right] . \tag{10}$$

In this approximation the predicted response is easily found from Eqs. (9) and (10),

$$\langle \dot{Q}(t)\rangle_{E(\tau)} = \sum_{n=1}^{\infty} \frac{\beta^n}{n!}\int_{-\infty}^{t} dt_1\cdots dt_n\, E(t_1)\cdots E(t_n)\langle \dot{Q}(t),\dot{Q}(t_1),\cdots,\dot{Q}(t_n)\rangle_0 . \tag{11}$$

The generalization of this result to the case of several external fields is straightforward. One finds

$$\langle \dot{Q}_i(t)\rangle_{\{E_j(\tau)\}} = \sum_{n=1}^{\infty} \frac{\beta^n}{n!} \sum_{i_1,\cdots,i_n} \int_{-\infty}^{t} dt_1\cdots dt_n\, E_{i_1}(t_1)\cdots E_{i_n}(t_n) \times \langle \dot{Q}_i(t),\dot{Q}_{i_1}(t_1),\cdots,\dot{Q}_{i_n}(t_n)\rangle_0 . \tag{12}$$

It is also easy to show that, in the case of one external field the response of an arbitrary degree of freedom A is given by

$$\langle A(t)\rangle_{E(\tau)} = \sum_{n=1}^{\infty} \frac{\beta^n}{n!} \int_{-\infty}^{t} dt_1 \cdots dt_n\, E(t_1)\cdots E(t_n) \langle A(t), \dot{Q}(t_1), \cdots, \dot{Q}(t_n)\rangle_0 \tag{13}$$

Equation (12) satisfies all 5 requirements for an approximate nonlinear response theory except, perhaps, time-reversal invariance. This requirement cannot be checked because Eq. (12) is not based on an expression for the path probability. On the other hand, there is no indication that Eq. (12) violates time-reversal invariance. Thus, Eq. (13) reduces to the correct expression in the linear limit which is not obvious since linear response theory is derived from time-reversal invariance. Furthermore, the second order term of Eq. (13) is also correct [8,13]. In many cases, of course, this term is zero.

As an application of Eq. (11) we now evaluate the nonlinear creep function. This quantity is defined as the average increase of Q in time t after a constant field E is introduced at t=0. Denoting the creep function by $\langle \Delta Q(t)\rangle_{E\,\theta(\tau)}$, we first note that Eq. (11) may be rewritten as

$$e^{\beta \int_{-\infty}^{t} E(\tau) \langle \dot{Q}(\tau)\rangle_{E(\tau')} d\tau} = \left\langle e^{\beta \int_{-\infty}^{t} E(\tau)\dot{Q}(\tau)\, d\tau} \right\rangle_0 . \tag{14}$$

Since $E(t)=E\,\theta(t)$ Eq. (14) implies for t>0

$$e^{\beta E \langle \Delta Q(t) \rangle_{E\theta(\tau)}} = \left\langle e^{\beta E \Delta Q(t)} \right\rangle_0 . \tag{15}$$

In the $E \to 0$ limit Eq. (15) reduces to the well-known expression for the linear creep function

$$\langle \Delta Q(t) \rangle_{E\theta(\tau)} = \frac{1}{2} \beta E \langle \Delta Q^2(t) \rangle_0 . \tag{16}$$

Equations (11)-(15) were derived for a Hamiltonian system but make sense also for a stochastic system. An example is random walk in one dimension. To calculate the right hand side of Eq. (15) we note that the number of jumps in time t is Poisson distributed around $N = \gamma_0 t$ where γ_0 is the zero field jump frequency. From this it is easy to see that Eq. (15) implies

$$e^{\beta E \langle \Delta Q(t) \rangle_{E\theta(\tau)}} = e^{\gamma_0 t [\cosh(\beta E a) - 1]} . \tag{17}$$

In this simple example there are no transient effects and the predicted average velocity is given by

$$\langle \dot{Q} \rangle_E = \gamma_0 a \, \frac{\cosh(\beta E a) - 1}{\beta E a} . \tag{18}$$

The theory predicts an exponential nonlinearity which is typical for random walks. For large fields the velocity varies as $\exp(\beta E a)$ whereas for the commonly used "symmetric" jump rate assignment one has asymptotically $\dot{Q} \propto \exp(\beta E a/2)$. On the other hand, for the "asymmetric" jump rate assignment $\gamma = \gamma_0 \exp(\beta E a)$ in the direction of the field and $\gamma = \gamma_0$ in the opposite direction, the predicted velocity is asymptotically correct. There are, however, many other possible jump rate assignments in an external field, and this illustrates well the impossibility of constructing a generally applicable approximate nonlinear response theory.

Another simple example of Eq. (15) is the case of a free particle in a box. It is a simple matter to evaluate $\langle e^{\beta E \Delta Q(t)} \rangle_0$ in the $t \to \infty$ limit where Q is the box length coordinate. If L denotes the length of the box, one finds

$$\lim_{t \to \infty} \left\langle e^{\beta E \Delta Q(t)} \right\rangle_0 = \left\langle e^{\beta E Q} \right\rangle \left\langle e^{-\beta E Q} \right\rangle = \frac{2\left[\cosh(\beta E L) - 1\right]}{(\beta E L)^2} \qquad (19)$$

where it has been assumed that Q(t) and Q(0) are uncorrelated for $t \to \infty$. For large fields Eq. (19) predicts an average displacement equal to L . The correct result is L/2 , of course. The theory gives a qualitatively correct result, for instance there is no drift of the particle after some time, but the result is not exact.

To summarize, the nonexistence of a useful exact nonlinear response theory raises the question whether any approximate nonlinear response theory exists. Five requirements have been proposed which such a theory should satisfy. It should, (1), calculate the response solely from a knowledge of the external field and of the equilibrium fluctuations of Q(t) . It should, (2), satisfy causality and, (3), time-reversal invariance, and also, (4), predict a linear response whenever the equilibrium fluctuations of Q(t) are gaussian. Finally, (5), if Q_1 and Q_2 fluctuate independently in equilibrium, a field coupling to Q_1 should not influence the Q_2-response and vice versa. It is not clear whether any theory exists which satisfies these five requirements. A candidate for such a theory has been proposed (Eq. (11), and more generally Eq. (12)). In deriving Eqs. (11) and (12) the external field density matrix was estimated by replacing the exact phase space paths by the unperturbed paths.

Whenever the cumulant averages of $Q(t)$ are smooth functions of time, the theory predicts the nonlinear effects to appear only some time after the field is introduced. This is a feature which is often seen in experiment where a system for a given external field may be almost linear on a short time scale while the DC response is strongly nonlinear [12].

The proposed approximate nonlinear response theory satisfies all five requirements except, perhaps, time-reversal invariance which cannot be checked. On the other hand, there are no indications of a violation of time-reversal invariance. Thus, the theory is exact to second order, which is as far as there are general results calculating the response from equilibrium fluctuations [14]. To properly check time-reversal invariance, the full path probability must be known. This is equivalent to knowing all cumulant averages of $\dot{Q}(t)$ in the external field. A possible generalization of Eq. (11) to the calculation of these averages is

$$\langle \dot{Q}(t_1), \cdots, \dot{Q}(t_n) \rangle_{E(\tau)} = \sum_{m=0}^{\infty} \frac{\beta^m}{m!} \int_{-\infty}^{t_n} dt_1' \cdots dt_m' \, E(t_1') \cdots E(t_m') \times \langle \dot{Q}(t_1), \cdots, \dot{Q}(t_n), \dot{Q}(t_1'), \cdots, \dot{Q}(t_m') \rangle_0 \quad (t_1 < \cdots < t_n) \tag{20}$$

with an obvious generalization to the case of several external fields. However, Eq. (20) explicitly violates causality which, as shown by Bochkov and Kuzovlev [14], implies the following exact relation between the various cumulant averages

$$\langle \dot{Q}(t) \rangle_{E(\tau)} = \sum_{n=1}^{\infty} (-1)^{n-1} \frac{\beta^n}{n!} \int_{-\infty}^{t} dt_1 \cdots dt_n \, E(t_1) \cdots E(t_n) \times \langle \dot{Q}(t), \dot{Q}(t_1), \cdots, \dot{Q}(t_n) \rangle_{E(\tau)} \quad . \tag{21}$$

It is an open problem whether it is possible to derive Eqs. (11) and (12) from a path probability that satisfies time-reversal invariance (Eq. (1)). Another open problem is to derive a criterion for the applicability of Eqs. (11) and (12). As a matter of fact it is not clear whether any system exists for which the proposed response theory is satisfactory. On the other hand it is likely that no other reasonable approximate nonlinear response theory exists. Thus, accepting requirement (4), the occurrence of a nonlinearity must be coupled to the existence of nonzero higher than second order equilibrium cumulant averages of $\dot{Q}(t)$. Similarly, requirement (5) more or less dictates the occurrence of cumulant averages in the expression for the response, since cumulants are additive for independently fluctuating degrees of freedom. Finally, in the case where $\{\dot{Q}_i\}$ is a vector, the transformation properties of the average $\{\langle \dot{Q}_i \rangle_E\}$ almost dictates the n'th order term to involve n+1 $\dot{Q}$'s .

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Vejledere: Stig Andur Pedersen, Helge Kragh og Ib Thiersen.
Nr. 38 er p.t. udgået.

39/81 "TIL KRITIKKEN AF VÆKSTØKONOMIEN".
Af: Jens Højgaard Jensen.

40/81 "TELEKOMMUNIKATION I DANMARK - oplæg til en teknologivurdering".
Projektrapport af: Arne Jørgensen, Bruno Petersen og Jan Vedde.
Vejleder: Per Nørgaard.

41/81 "PLANNING AND POLICY CONSIDERATIONS RELATED TO THE INTRODUCTION OF RENEWABLE ENERGY SOURCES INTO ENERGY SUPPLY SYSTEMS".
ENERGY SERIES NO. 3.
Af: Bent Sørensen.

42/81 "VIDENSKAB TEORI SAMFUND - En introduktion til materialistiske videnskabsopfattelser".
Af: Helge Kragh og Stig Andur Pedersen.

43/81 1."COMPARATIVE RISK ASSESSMENT OF TOTAL ENERGY SYSTEMS".
2."ADVANTAGES AND DISADVANTAGES OF DECENTRALIZATION".
ENERGY SERIES NO. 4.
Af: Bent Sørensen.

44/81 "HISTORISKE UNDERSØGELSER AF DE EKSPERIMENTELLE FORUDSÆTNINGER FOR RUTHERFORDS ATOMMODEL".
Projektrapport af: Niels Thor Nielsen.
Vejleder: Bent C. Jørgensen.

45/82 Er aldrig udkommet.

46/82 "EKSEMPLARISK UNDERVISNING OG FYSISK ERKENDESE-
1+11 ILLUSTRERET VED TO EKSEMPLER".
Projektrapport af: Torben O.Olsen, Lasse Rasmussen og Niels Dreyer Sørensen.
Vejleder: Bent C. Jørgensen.

47/82 "BARSEBÄCK OG DET VÆRST OFFICIELT-TÆNKELIGE UHELD".
ENERGY SERIES NO. 5.
Af: Bent Sørensen.

48/82 "EN UNDERSØGELSE AF MATEMATIKUNDERVISNINGEN PÅ ADGANGSKURSUS TIL KØBENHAVNS TEKNIKUM".
Projektrapport af: Lis Eilertzen, Jørgen Karrebæk, Troels Lange, Preben Nørregaard, Lissi Pedesen, Laust Rishøj, Lill Røn og Isac Showiki.
Vejleder: Mogens Niss.

49/82 "ANALYSE AF MULTISPEKTRALE SATELLITBILLEDER".
Projektrapport af: Preben Nørregaard.
Vejledere: Jørgen Larsen og Rasmus Ole Rasmussen.

50/82 "HERSLEV - MULIGHEDER FOR VEDVARENDE ENERGI I EN LANDSBY".
ENERGY SERIES NO. 6.
Rapport af: Bent Christensen, Bent Hove Jensen, Dennis B. Møller, Bjarne Laursen, Bjarne Lillethorup og Jacob Mørch Pedersen.
Vejleder: Bent Sørensen.

51/82 "HVAD KAN DER GØRES FOR AT AFHJÆLPE PIGERS BLOKERING OVERFOR MATEMATIK ?"
Projektrapport af: Lis Eilertzen, Lissi Pedersen, Lill Røn og Susanne Stender.

52/82 "DESUSPENSION OF SPLITTING ELLIPTIC SYMBOLS".
Af: Bernhelm Booss og Krzysztof Wojciechowski.

53/82 "THE CONSTITUTION OF SUBJECTS IN ENGINEERING EDUCATION".
Af: Arne Jacobsen og Stig Andur Pedersen.

54/82 "FUTURES RESEARCH" - A Philosophical Analysis of Its Subject-Matter and Methods.
Af: Stig Andur Pedersen og Johannes Witt-Hansen.

55/82 "MATEMATISKE MODELLER" - Litteratur på Roskilde Universitetsbibliotek.
En biografi.
Af: Else Høyrup.

Vedr. tekst nr. 55/82 se også tekst nr. 62/83.

56/82 "EN - TO - MANGE" -
En undersøgelse af matematisk økologi.
Projektrapport af: Troels Lange.
Vejleder: Anders Madsen.

57/83 "ASPECT EKSPERIMENTET"-
Skjulte variable i kvantemekanikken?
Projektrapport af: Tom Juul Andersen.
Vejleder: Peder Voetmann Christiansen.
Nr. 57 er udgået.

58/83 "MATEMATISKE VANDRINGER" - Modelbetragtninger over spredning af dyr mellem småbiotoper i agerlandet.
Projektrapport af: Per Hammershøj Jensen og Lene Vagn Rasmussen.
Vejleder: Jørgen Larsen.

59/83 "THE METHODOLOGY OF ENERGY PLANNING".
ENERGY SERIES NO. 7.
Af: Bent Sørensen.

60/83 "MATEMATISK MODEKSPERTISE"- et eksempel.
Projektrapport af: Erik O. Gade, Jørgen Karrebæk og Preben Nørregaard.
Vejleder: Anders Madsen.

61/83 "FYSIKS IDEOLOGISKE FUNKTION, SOM ET EKSEMPEL PÅ EN NATURVIDENSKAB - HISTORISK SET".
Projektrapport af: Annette Post Nielsen.
Vejledere: Jens Høyrup, Jens Højgaard Jensen og Jørgen Vogelius.

62/83 "MATEMATISKE MODELLER" - Litteratur på Roskilde Universitetsbibliotek.
En biografi 2. rev. udgave.
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Af: David Crossley og Bent Sørensen.

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Af: Berhelm Booss og Jens Høyrup.

65/83 "ANVENDT MATEMATIK - TEORI ELLER PRAKSIS".
Projektrapport af: Per Hedegård Andersen, Kirsten Habekost, Carsten Holst-Jensen, Annelise von Moos, Else Marie Pedersen og Erling Møller Pedersen.
Vejledere: Bernhelm Booss og Klaus Grünbaum.

66/83 "MATEMATISKE MODELLER FOR PERIODISK SELEKTION I ESCHERICHIA COLI".
Projektrapport af: Hanne Lisbet Andersen, Ole Richard Jensen og Klavs Frisdahl.
Vejledere: Jørgen Larsen og Anders Hede Madsen.

67/83 "ELEPSOIDE METODEN - EN NY METODE TIL LINEÆR PROGRAMMERING?"
Projektrapport af: Lone Biilmann og Lars Boye.
Vejleder: Mogens Brun Heefelt.

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- til kritikken af teoriladede modeller.
Projektrapport af: Lise Odgård Gade, Susanne Hansen, Michael Hviid og Frank Mølgård Olsen.
Vejleder: Jørgen Larsen.

69/83 "ELEVFORUDSÆTNINGER I FYSIK"
- en test i 1.g med kommentarer.

Af: Albert C. Paulsen.

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Projektrapport af: Hanne Lisbet Andersen, Torben J. Andreasen, Svend Åge Houmann, Helle Glerup Jensen, Keld Fl. Nielsen, Lene Vagn Rasmussen.
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Af: Peder Voetmann Christiansen.

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ENERGY SERIES NO. 9
Specialeopgave i fysik af: Bent Hove Jensen.
Vejleder: Bent Sørensen.

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Projektrapport af: Bodil Harder og Linda Szkotak Jensen.
Vejledere: Jens Højgaard Jensen og Bent C. Jørgensen.

75/84 "MATEMATIKUNDERVISNINGEN I FREMTIDENS GYMNASIUM"
- Case: Lineær programmering.
Projektrapport af: Morten Blomhøj, Klavs Frisdahl og Frank Mølgaard Olsen.
Vejledere: Mogens Brun Heefelt og Jens Bjørneboe.

76/84 "KERNEKRAFT I DANMARK?" - Et høringssvar indkaldt af miljøministeriet, med kritik af miljøstyrelsens rapporter af 15. marts 1984.
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Af: Niels Boye Olsen og Bent Sørensen.

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Opinionsundersøgelser belyst ved statistiske modeller.
Projektrapport af: Svend Åge Houmann, Keld Nielsen og Susanne Stender.
Vejledere: Jørgen Larsen og Jens Bjørneboe.

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Specialrapport af: Hans Hedal, Frank C. Ludvigsen og Finn C. Physant.
Vejleder: Niels Boye Olsen.

79/84 "MATEMATIK OG ALMENDANNELSE".
Projektrapport af: Henrik Coster, Mikael Wennerberg Johansen, Povl Kattler, Birgitte Lydholm og Morten Overgaard Nielsen.
Vejleder: Bernhelm Booss.

80/84 "KURSUSMATERIALE TIL MATEMATIK B".
Af: Mogens Brun Heefelt.

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Specialerapport af: Jørgen Wind Petersen og Jan Christensen.
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Rapport fra et seminar afholdt i Hvidovre 25-27 april 1983.
Red.: Jens Højgaard Jensen, Bent C. Jørgensen og Mogens Niss.

83/84 "ON THE QUANTIFICATION OF SECURITY":
PEACE RESEARCH SERIES NO. 1
Af: Bent Sørensen
nr. 83 er p.t. udgået

84/84 "NOGLE ARTIKLER OM MATEMATIK, FYSIK OG ALMENDANNELSE".
Af: Jens Højgaard Jensen, Mogens Niss m. fl.

85/84 "CENTRIFUGALREGULATORER OG MATEMATIK".
Specialerapport af: Per Hedegård Andersen, Carsten Holst-Jensen, Else Marie Pedersen og Erling Møller Pedersen.
Vejleder: Stig Andur Pedersen.

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91/85 "KVANTETEORI FOR GYMNASIET".
1. Lærervejledning
Projektrapport af: Biger Lundgren, Henning Sten Hansen og John Johansson.
Vejleder: Torsten Meyer.

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2. Materiale
Projektrapport af: Biger Lundgren, Henning Sten Hansen og John Johansson.
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Af: Peder Voetmann Christiansen.

94/85 "TREENIGHEDEN BOURBAKI - generalen, matematikeren og ånden".
Projektrapport af: Morten Blomhøj, Klavs Frisdahl og Frank M. Olsen.
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Vejleder: Bent Sørensen.

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Af: Jeppe C. Dyre.

98/85 "VALGMULIGHEDER I INFORMATIONSALDEREN".
Af: Bent Sørensen.

99/85 "Der er langt fra Q til R".
Projektrapport af: Niels Jørgensen og Mikael Klintorp.
Vejleder: Stig Andur Pedersen.

100/85 "TALSYSTEMETS OPBYGNING".
Af: Mogens Niss.

101/85 "EXTENDED MOMENTUM THEORY FOR WINDMILLS IN PERTURBATIVE FORM".
Af: Ganesh Sengupta.

102/85 OPSTILLING OG ANALYSE AF MATEMATISKE MODELLER, BELYST VED MODELLER OVER KØERS FODEROPTAGELSE OG - OMSÆTNING".
Projektrapport af: Lis Eilertzen, Kirsten Habekost, Lill Røn og Susanne Stender.
Vejleder: Klaus Grünbaum.

103/85 "ØDSLE KOLDKRIGERE OG VIDENSKABENS LYSE IDEER".
Projektrapport af: Niels Ole Dam og Kurt Jensen.
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104/85 "ANALOGREGNEMASKINEN OG LORENZLIGNINGER".
Af: Jens Jæger.

105/85 "THE FREQUENCY DEPENDENCE OF THE SPECIFIC HEAT AF THE GLASS REANSITION".
Af: Tage Christensen.

"A SIMPLE MODEL AF AC HOPPING CONDUCTIVITY".
Af: Jeppe C. Dyre.
Contributions to the Third International Conference on the Structure of Non - Crystalline Materials held in Grenoble July 1985.

106/85 "QUANTUM THEORY OF EXTENDED PARTICLES".
Af: Bent Sørensen.

107/85 "EN MYG GØR INGEN EPIDEMI".
- flodblindhed som eksempel på matematisk modellering af et epidemiologisk problem.
Projektrapport af: Per Hedegård Andersen, Lars Boye, CarstenHolst Jensen, Else Marie Pedersen og Erling Møller Pedersen.
Vejleder: Jesper Larsen.

108/85 "APPLICATIONS AND MODELLING IN THE MATEMATICS CUR - RICULUM" - state and trends -
Af: Mogens Niss.

109/85 "COX I STUDIETIDEN" - Cox's regressionsmodel anvendt på studenteroplysninger fra RUC.
Projektrapport af: Mikael Wennerberg Johansen, Poul Katler og Torben J. Andreasen.
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110/85 "PLANNING FOR SECURITY".
Af: Bent Sørensen

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Projektrapport af: Birgit Andresen, Beatriz Quinones og Jimmy Staal.
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112/85 "VIDENSKABELIGGØRELSE AF DANSK TEKNOLOGISK INNOVATION FREM TIL 1950 - BELYST VED EKSEMPLER".
Projektrapport af: Erik Odgaard Gade, Hans Hedal, Frank C. Ludvigsen, Annette Post Nielsen og Finn Physant.
Vejleder: Claus Bryld og Bent C. Jørgensen.

113/85 "DESUSPENSION OF SPLITTING ELLIPTIC SYMBOLS 11".
Af: Bernhelm Booss og Krzysztof Wojciechowski.

114/85 "ANVENDELSE AF GRAFISKE METODER TIL ANALYSE AF KONTIGENSTABELLER".
Projektrapport af: Lone Biilmann, Ole R. Jensen og Anne-Lise von Moos.
Vejleder: Jørgen Larsen.

115/85 "MATEMATIKKENS UDVIKLING OP TIL RENESSANCEN".
Af: Mogens Niss.

116/85 "A PHENOMENOLOGICAL MODEL FOR THE MEYER-NELDEL RULE".
Af: Jeppe C. Dyre.

117/85 "KRAFT & FJERNVARMEOPTIMERING"
Af: Jacob Mørch Pedersen.
Vejleder: Bent Sørensen

118/85 "TILFÆLDIGHEDEN OG NØDVENDIGHEDEN IFØLGE PEIRCE OG FYSIKKEN".
Af: Peder Voetmann Christiansen

119/86 "DET ER GANSKE VIST - - EUKLIDS FEMTE POSTULAT KUNNE NOK SKABE RØRE I ANDEDAMMEN".
Af: Iben Maj Christiansen
Vejleder: Mogens Niss.

120/86 "ET ANTAL STATISTISKE STANDARDMODELLER".
Af: Jørgen Larsen

121/86 "SIMULATION I KONTINUERT TID".
Af: Peder Voetmann Christiansen.

122/86 "ON THE MECHANISM OF GLASS IONIC CONDUCTIVITY".
Af: Jeppe C. Dyre.

123/86 "GYMNASIEFYSIKKEN OG DEN STORE VERDEN".
Fysiklærerforeningen, IMFUFA, RUC.

124/86 "OPGAVESAMLING I MATEMATIK".
Samtlige opgaver stillet i tiden 1974-jan. 1986.

125/86 "UVBY,β - systemet - en effektiv fotometrisk spektralklassifikation af B-,A- og F-stjerner".
Projektrapport af: Birger Lundgren.

126/86 "OM UDVIKLINGEN AF DEN SPECIELLE RELATIVITETSTEORI".
Projektrapport af: Lise Odgaard & Linda Szkotak Jensen
Vejledere: Karin Beyer & Stig Andur Pedersen.

127/86 "GALOIS' BIDRAG TIL UDVIKLINGEN AF DEN ABSTRAKTE ALGEBRA".
Projektrapport af: Pernille Sand, Heine Larsen & Lars Frandsen.
Vejleder: Mogens Niss.

128/86 "SMÅKRYB" - om ikke-standard analyse.
Projektrapport af: Niels Jørgensen & Mikael Klintorp.
Vejleder: Jeppe Dyre.

129/86 "PHYSICS IN SOCIETY"
Lecture Notes 1983 (1986)
Af: Bent Sørensen

130/86 "Studies in Wind Power"
Af: Bent Sørensen

131/86 "FYSIK OG SAMFUND" - Et integreret fysik/historieprojekt om naturanskuelsens historiske udvikling og dens samfundsmæssige betingethed.
Projektrapport af: Jakob Heckscher, Søren Brønd, Andy Wierød.
Vejledere: Jens Høyrup, Jørgen Vogelius, Jens Højgaard Jensen.

132/86 "FYSIK OG DANNELSE"
Projektrapport af: Søren Brønd, Andy Wierød.
Vejledere: Karin Beyer, Jørgen Vogelius.

133/86 "CHERNOBYL ACCIDENT: ASSESSING THE DATA.
ENERGY SERIES NO. 15.
AF: Bent Sørensen.

134/87 "THE D.C. AND THE A.C. ELECTRICAL TRANSPORT IN AsSeTe SYSTEM"
Authors: M.B.El-Den, N.B.Olsen, Ib Høst Pedersen, Petr Visčor

135/87 "INTUITIONISTISK MATEMATIKS METODER OG ERKENDELSESTEORETISKE FORUDSÆTNINGER"
MASTEMATIKSPECIALE: Claus Larsen
Vejledere: Anton Jensen og Stig Andur Pedersen

136/87 "Mystisk og naturlig filosofi: En skitse af kristendommens første og andet møde med græsk filosofi"
Projektrapport af Frank Colding Ludvigsen
Vejledere: Historie: Ib Thiersen
Fysik: Jens Højgaard Jensen

137/87 "HOPMODELLER FOR ELEKTRISK LEDNING I UORDNEDE FASTE STOFFER" - Resume af licentiatafhandling
Af: Jeppe Dyre
Vejledere: Niels Boye Olsen og Peder Voetmann Christiansen.

138/87 "JOSEPHSON EFFECT AND CIRCLE MAP."

Paper presented at the International Workshop on Teaching Nonlinear Phenomena at Universities and Schools, "Chaos in Education". Balaton, Hungary, 26 April-2 May 1987.

By: Peder Voetmann Christiansen

139/87 "Machbarkeit nichtbeherrschbarer Technik durch Fortschritte in der Erkennbarkeit der Natur"

Af: Bernhelm Booss-Bavnbek
Martin Bohle-Carbonell

140/87 "ON THE TOPOLOGY OF SPACES OF HOLOMORPHIC MAPS"

By: Jens Gravesen

141/87 "RADIOMETERS UDVIKLING AF BLODGASAPPARATUR - ET TEKNOLOGIHISTORISK PROJEKT"

Projektrapport af Finn C. Physant

Vejleder: Ib Thiersen

142/87 "The Calderón Projektor for Operators With Splitting Elliptic Symbols"

by: Bernhelm Booss-Bavnbek og
Krzysztof P. Wojciechowski

143/87 "Kursusmateriale til Matematik på NAT-BAS"

af: Mogens Brun Heefelt

144/87 "Context and Non-Locality - A Peircan Approach

Paper presented at the Symposium on the Foundations of Modern Physics The Copenhagen Interpretation 60 Years after the Como Lecture. Joensuu, Finland, 6 - 8 august 1987.

By: Peder Voetmann Christiansen

145/87 "AIMS AND SCOPE OF APPLICATIONS AND MODELLING IN MATHEMATICS CURRICULA"

Manuscript of a plenary lecture delivered at ICMTA 3, Kassel, FRG 8.-11.9.1987

By: Mogens Niss

146/87 "BESTEMMELSE AF BULKRESISTIVITETEN I SILICIUM"

- en ny frekvensbaseret målemetode.

Fysikspeciale af Jan Vedde

Vejledere: Niels Boye Olsen & Petr Viščor

147/87 "Rapport om BIS på NAT-BAS"

redigeret af: Mogens Brun Heefelt

148/87 "Naturvidenskabsundervisning med Samfundsperspektiv"

af: Peter Colding-Jørgensen DLH
Albert Chr. Paulsen

149/87 "In-Situ Measurements of the density of amorphous germanium prepared in ultra high vacuum"

by: Petr Viščor

150/87 "Structure and the Existence of the first sharp diffraction peak in amorphous germanium prepared in UHV and measured in-situ"

by: Petr Viščor

151/87 "DYNAMISK PROGRAMMERING"

Matematikprojekt af:
Birgit Andresen, Keld Nielsen og Jimmy Staal

Vejleder: Mogens Niss

152/87 "PSEUDO-DIFFERENTIAL PROJECTIONS AND THE TOPOLOGY OF CERTAIN SPACES OF ELLIPTIC BOUNDARY VALUE PROBLEMS"

by: Bernhelm Booss-Bavnbek
Krzysztof P. Wojciechowski

153/88 "HALVLEDERTEKNOLOGIENS UDVIKLING MELLEM MILITÆRE OG CIVILE KRÆFTER"

Et eksempel på humanistisk teknologihistorie
Historiespeciale

Af: Hans Hedal

Vejleder: Ib Thiersen

154/88 "MASTER EQUATION APPROACH TO VISCOUS LIQUIDS AND THE GLASS TRANSITION"

By: Jeppe Dyre

155/88 "A NOTE ON THE ACTION OF THE POISSON SOLUTION OPERATOR TO THE DIRICHLET PROBLEM FOR A FORMALLY SELFADJOINT DIFFERENTIAL OPERATOR"

by: Michael Pedersen

156/88 "THE RANDOM FREE ENERGY BARRIER MODEL FOR AC CONDUCTION IN DISORDERED SOLIDS"

by: Jeppe C. Dyre

157/88 " STABILIZATION OF PARTIAL DIFFERENTIAL EQUATIONS BY FINITE DIMENSIONAL BOUNDARY FEEDBACK CONTROL: A pseudo-differential approach."

by: Michael Pedersen

158/88 "UNIFIED FORMALISM FOR EXCESS CURRENT NOISE IN RANDOM WALK MODELS"

by: Jeppe Dyre

159/88 "STUDIES IN SOLAR ENERGY"

by: Bent Sørensen

160/88 "LOOP GROUPS AND INSTANTONS IN DIMENSION TWO"

by: Jens Gravesen

161/88 "PSEUDO-DIFFERENTIAL PERTURBATIONS AND STABILIZATION OF DISTRIBUTED PARAMETER SYSTEMS:

Dirichlet feedback control problems"

by: Michael Pedersen

162/88 "PIGER & FYSIK - OG MEGET MERE"

AF: Karin Beyer, Sussanne Blegaa, Birthe Olsen,
Jette Reich , Mette Vedelsby

163/88 "EN MATEMATISK MODEL TIL BESTEMMELSE AF PERMEABILITETEN FOR BLOD-NETHINDE-BARRIEREN"

Af: Finn Langberg, Michael Jarden, Lars Frellesen

Vejleder: Jesper Larsen

164/88 "Vurdering af matematisk teknologi
Technology Assessment
Technikfolgenabschätzung"

Af: Bernhelm Booss-Bavnbek, Glen Pate med
Martin Bohle-Carbonell og Jens Højgaard Jensen

165/88 "COMPLEX STRUCTURES IN THE NASH-MOSER CATEGORY"

by: Jens Gravesen

166/88 "Grundbegreber i Sandsynligheds-
regningen"

Af: Jørgen Larsen

167a/88 "BASISSTATISTIK 1. Diskrete modeller"

Af: Jørgen Larsen

167b/88 "BASISSTATISTIK 2. Kontinuerte
modeller"

Af: Jørgen Larsen

168/88 "OVERFLADEN AF PLANETEN MARS"
Laboratorie-simulering og MARS-analoger
undersøgt ved Mössbauerspektroskopi.

Fysikspeciale af:

Birger Lundgren

Vejleder: Jens Martin Knudsen
Fys.Lab./HCØ

169/88 "CHARLES S. PEIRCE: MURSTEN OG MØRTEL
TIL EN METAFYSIK."

Fem artikler fra tidsskriftet "The Monist"
1891-93.

Introduktion og oversættelse:

Peder Voetmann Christeansen

170/88 "OPGAVESAMLING I MATEMATIK"

Samtlige opgaver stillet i tiden
1974 - juni 1988

171/88 "The Dirac Equation with Light-Cone Data"

af: Johnny Tom Ottesen

172/88 "FYSIK OG VIRKELIGHED"

Kvantemekanikkens grundlagsproblem
i gymnasiet.

Fysikprojekt af:

Erik Lund og Kurt Jensen

Vejledere: Albert Chr. Paulsen og
Peder Voetmann Christiansen

173/89 "NUMERISKE ALGORITMER"

af: Mogens Brun Heefelt

174/89 " GRAFISK FREMSTILLING AF
FRAKTALER OG KAOS"

af: Peder Voetmann Christiansen

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DEPENDENT SPECTRUM OF THE NON-STATONARY
SOLUTION TO THE OPERATOR RICCATI EQUATION

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RESPONSE THEORY"

af : Jeppe Dyre

177/89 "HVAD SKAL ADAM STÅ MODEL TIL"

af: Morten Andersen, Ulla Engström,
Thomas Gravesen, Nanna Lund, Pia
Madsen, Dina Rawat, Peter Torstensen

Vejleder: Mogens Brun Heefelt

178/89 "BIOSYNTESEN AF PENICILLIN - en matematisk model"

af: Ulla Eghave Rasmussen, Hans Oxvang Mortensen,
Michael Jarden

vejleder i matematik: Jesper Larsen
biologi: Erling Lauridsen

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