

MARTIN A. NOWAK

Curriculum Vitae

Personal Information

Name: Martin Andreas Nowak

Address: Program for Evolutionary Dynamics, Harvard University
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Phone: (617) 496-4737 Fax (617) 496-4629

Degrees: M.Sc. Vienna, Ph.D. Vienna, M.A. Oxford, M.A. Harvard

Current position

Professor of Biology and Mathematics, Harvard University

Director, Program for Evolutionary Dynamics, Harvard University

Education

1975-1983 Albertus Magnus Gymnasium in Vienna
1983-1989 University of Vienna, studying Biochemistry and Mathematics
1985 First Diploma: Biochemistry (first class honors)
1987 Diploma thesis: Theoretical Chemistry
1987 Second Diploma: Biochemistry (first class honors; finished one year faster)
1987-1989 Doctoral thesis: Mathematics
1989 Final exams for degree *Doctor rerum naturalium* (with highest honors)

Scientific career

Vienna:

1987-1988 Institute for Theoretical Chemistry, Peter Schuster
1987-1989 Institute for Mathematics, Karl Sigmund
1988 Max Planck Institute for Biophysical Chemistry, Göttingen, Manfred Eigen
1993 "Habilitation" at the Institute of Mathematics, University of Vienna

Oxford:

1989-1990 Erwin Schrödinger Scholarship to work with Robert May (Lord May of Oxford)

1990-1992 Guy Newton Junior Research Fellow, Wolfson College
1991 Royal Society Research Grant
1992-1998 Wellcome Trust Senior Research Fellow in Biomedical Sciences
1993-1996 E. P. Abraham Junior Research Fellow, Keble College
1995-1998 Head of Mathematical Biology Group
1996-1998 Senior Research Fellow, Keble College
1997-1998 Professor of Mathematical Biology

Princeton:

1998-2003 Head, Program in Theoretical Biology, Institute for Advanced Study
1999-2003 Associated Faculty, Princeton University, Ecology and Evolutionary Biology
2000-2003 Associated Faculty, Princeton University, Program in Applied and Computational Mathematics

Harvard:

2003- Professor of Biology and Mathematics,
Director, Program for Evolutionary Dynamics

Prizes, Named Lectures, Memberships

1990 *Promotion sub auspiciis praesidentis rei publicae* (a distinction given to people who have passed all major exams during school and university with the best mark)
1990 Prize from the Austrian Science Minister
1995 Richardson Lecture, Keble College
1996 Weldon Memorial Prize (given every 2-3 years for outstanding contributions to Biometric Science; previous winners include: Ronald Fisher, JBS Haldane, Sewall Wright, Motoo Kimura, Robert May, David Cox)
1997 Shanks Lecture, Vanderbilt University, Nashville, Tennessee
1998 Albert Wander Prize and Memorial Lecture, University of Bern, Switzerland
1999 Porter Lecture, Rice University, Houston, Texas
1999 Erwin Schrodinger Lecture, University of Vienna, Austria
1999 Akira Okubo Prize, International and Japanese Society for Mathematical Biology
1999 Roger F. Murray Prize, Institute for Quantitative Research in Finance
2000 Gergen Lecture, Duke University
2001 Benjamin Pinkel Lecture, University of Pennsylvania
2001 Corresponding Member, Austrian Academy of Sciences

- 2001 Rainich Lectures, University of Michigan, Ann Arbor
- 2001 David Starr Jordan Prize, Stanford University, Cornell University, Indiana University
- 2003 Henry Dale Prize, The Royal Institution, London
- 2006 Invited Lecture, Congress for Mathematics, Madrid
- 2006 R.R. Hawkins Award for *Evolutionary Dynamics*, Professional and Scholarly Publishing Division of the American Association of Publishers
- 2007 Radon Lecture, Austrian Academy of Sciences
- 2008 Coxeter Lectures, Fields Institute, Toronto

Research Interests

Evolutionary dynamics

Somatic evolution of cancer, genetic instability

Molecularly targeted anti-cancer therapy

Infectious diseases, immunology, virus dynamics

Quasispecies theory

Genetic redundancy

Evolutionary game theory

Adaptive dynamics

Finite populations

Evolutionary graph theory

Evolution of language

Cooperation, fairness, reputation

Indirect reciprocity

Group selection

Experimental games

Origin of evolution, prelife

Publications

Books

Nowak M, RM May (2000). *Virus Dynamics: Mathematical Principles of Immunology and Virology*. Oxford: Oxford University Press.

Nowak MA (2006). *Evolutionary Dynamics: Exploring the Equations of Life*. Cambridge, MA: Harvard University Press.

Selected Publications

Rand DG, A Dreber, T Ellingsen, D Fudenberg, MA Nowak (2009). Positive interactions promote public cooperation. *Science* 325: 1272-1275.

Tarnita CE, T Antal, H Ohtsuki, MA Nowak (2009). Evolutionary dynamics in set structured populations. *P Natl Acad Sci USA* 106: 8601-8604.

Antal T, H Ohtsuki, J Wakeley, PD Taylor, MA Nowak (2009). Evolution of cooperation by phenotypic similarity. *P Natl Acad Sci USA* 106: 8597-8600.

Ohtsuki H, Y Iwasa, MA Nowak (2009). Indirect reciprocity provides only a narrow margin for efficiency for costly punishment. *Nature* 457: 79-82.

Dreber A, DG Rand, D Fudenberg, MA Nowak (2008). Winners don't punish. *Nature* 452: 348-351.

Nowak MA, H Ohtsuki (2008). Prevolutionary dynamics and the origin of evolution. *P Natl Acad Sci USA* 105: 14924-14927.

Hauert C, A Traulsen, H Brandt, MA Nowak, K Sigmund (2007). Via freedom to coercion: The emergence of costly punishment. *Science* 316: 1905-1907.

Lieberman E, JB Michel, J Jackson, T Tang, MA Nowak (2007). Quantifying the evolutionary dynamics of language. *Nature* 449: 713-716.

Nowak MA (2006). Five rules for the evolution of cooperation. *Science* 314: 1560-1563.

Nowak MA (2006). *Evolutionary Dynamics: Exploring the Equations of Life*. Cambridge, MA: Harvard University Press. (Excerpt, Nature review, Science review, R.R. Hawkins Award).

Ohtsuki H, C Hauert, E Lieberman, MA Nowak (2006). A simple rule for the evolution of cooperation on graphs and social networks. *Nature* 441: 502-505.

Lieberman E, C Hauert, MA Nowak (2005). Evolutionary dynamics on graphs. *Nature* 433: 312-316.

Michor F, TP Hughes, Y Iwasa, S Branford, NP Shah, CL Sawyers, MA Nowak (2005). Dynamics of chronic myeloid leukemia. *Nature* 435: 1267-1270.

Nowak MA, K Sigmund (2005). Evolution of indirect reciprocity. *Nature* 437: 1291-1298.

Nowak MA, F Michor, Y Iwasa (2004). Evolutionary dynamics of tumor suppressor gene inactivation. *P Natl Acad Sci USA* 101: 10635-10638.

Nowak MA, A Sasaki, C Taylor, D Fudenberg (2004). Emergence of cooperation and evolutionary stability in finite populations. *Nature* 428: 646-650.

Nowak MA, K Sigmund (2004). Evolutionary dynamics of biological games. *Science* 303: 793-799

Wei X, JM Decker, S Wang, H Hui, JC Kappes, W Xiaoyun, JF Salazar, MG Salazar, JM Kilby, MS Saag, NL Komarova, MA Nowak, BH Hahn, PD Kwong, GM Shaw (2003). Antibody neutralization and escape by HIV-1. *Nature* 422: 307-312.

Nowak MA, NL Komarova, P Niyogi (2002). Computational and evolutionary aspects of language. *Nature* 417: 611-617.

Nowak MA, NL Komarova, A Sengupta, PF Jallepalli, IM Shih, B Vogelstein, C Lengauer (2002). The role of chromosomal instability in tumor initiation. *P Natl Acad Sci USA* 99: 16226-16231.

Nowak MA, NL Komarova, P Niyogi (2001). Evolution of universal grammar. *Science* 291: 114-118.

Nowak M, RM May (2000). *Virus Dynamics: Mathematical Principles of Immunology and Virology*. Oxford University Press.

Nowak MA, KM Page, K Sigmund (2000). Fairness versus reason in the ultimatum game. *Science* 289: 1773-1775.

Nowak MA, JB Plotkin, VAA Jansen (2000). The evolution of syntactic communication. *Nature* 404: 495-498.

Nowak MA, D Krakauer (1999). The evolution of language. *P Natl Acad Sci USA* 96: 8028-8033.

Nowak MA, K Sigmund (1998). Evolution of indirect reciprocity by image scoring. *Nature* 393: 573-577.

Bonhoeffer S, RM May, GM Shaw, MA Nowak (1997). Virus dynamics and drug therapy. *P Natl Acad Sci USA* 94: 6971-6976.

Nowak MA, MC Boerlijst, J Cooke, J Maynard Smith (1997). Evolution of genetic redundancy. *Nature* 388: 167-171.

Nowak MA, CRM Bangham (1996). Population dynamics of immune responses to persistent viruses. *Science* 272: 74-79.

Nowak MA, S Bonhoeffer, AM Hill, R Boehme, HC Thomas, H McDade (1996). Viral dynamics in hepatitis B virus infection. *P Natl Acad Sci USA* 93: 4398-4402.

Nowak MA, RM May, RE Phillips, S Rowland-Jones, DG Lalloo, S McAdam, P Klenerman, B Köppe, K Sigmund, CRM Bangham, AJ McMichael (1995). Antigenic oscillations and shifting immunodominance in HIV-1 infections. *Nature* 375: 606-611.

Wei X, SK Ghosh, ME Taylor, VA Johnson, EA Emini, P Deutsch, JD Lifson, S Bonhoeffer, MA Nowak, BH Hahn, MS Saag, GM Shaw (1995). Viral dynamics in human immunodeficiency virus type 1 infection. *Nature* 373: 117-122.

Nowak MA, RM May (1994). Superinfection and the evolution of parasite virulence. *Proc R Soc B* 255: 81-89.

Tilman D, RM May, CL Lehman, MA Nowak (1994). Habitat destruction and the extinction debt. *Nature* 371: 65-66.

Nowak MA, K Sigmund (1993). A strategy of win-stay, lose-shift that outperforms tit for tat in the Prisoner's Dilemma game. *Nature* 364: 56-58.

Nowak MA, RM May (1992). Evolutionary games and spatial chaos. *Nature* 359: 826-829.

Nowak MA, K Sigmund (1992). Tit for tat in heterogeneous populations. *Nature* 355: 250-253.

Nowak MA, RM Anderson, AR McLean, TFW Wolfs, J Goudsmit, RM May (1991). Antigenic diversity thresholds and the development of AIDS. *Science* 254: 963-969.

Articles in Scientific American and Natural History

Nowak MA, RM May, K Sigmund (1995). The arithmetics of mutual help. *Sci Am* 272: 76-81.

Nowak MA, AJ McMichael (1995). How HIV defeats the immune system. *Sci Am* 273: 58-65.

Nowak MA (2000). Homo Grammaticus. *Nat Hist* 109: 36-44.

Sigmund K, K Fehr, MA Nowak (2002). The economics of fair play. *Sci Am* 286: 82-87.

All Publications

1989

1. Nowak M, P Schuster (1989). Error thresholds of replication in finite populations: Mutation frequencies and the onset of Muller's ratchet. *J theor Biol* 137: 375-395.
2. Nowak M, K Sigmund (1989). Game-dynamical aspects of the prisoner's dilemma. *Appl Math Comp* 30: 191-213.
3. Nowak M, K Sigmund (1989). Oscillations in the evolution of reciprocity. *J theor Biol* 137: 21-26.

1990

4. Nowak MA (1990). An evolutionarily stable strategy may be inaccessible. *J theor Biol* 142: 237-241.
5. Nowak M (1990). HIV mutation rate. *Nature* 347: 522.
6. Nowak M (1990). Stochastic strategies in the prisoner's dilemma. *Theor Pop Biol* 38: 93-112.
7. Nowak MA, RM May, RM Anderson (1990). The evolutionary dynamics of HIV quasispecies and the development of immunodeficiency disease. *AIDS* 4: 1095-1103.
8. Nowak M, K Sigmund (1990). The evolution of stochastic strategies in the prisoner's dilemma. *Acta Appl Math* 20: 247-265.

1991

9. Kwiatkowski D, M Nowak (1991). Periodic and chaotic host-parasite interactions in human malaria.

P Natl Acad Sci USA 88: 5111-5113.

10. Magurran AE, MA Nowak (1991). Another battle of the sexes: the consequences of sexual asymmetry in mating costs and predation risk in the guppy, *Poecilia reticulata*. *Proc R Soc B* 246: 31-38.
11. Nowak M (1991). The evolution of viruses. Competition between horizontal and vertical transmission of mobile genes. *J theor Biol* 150: 339-347.
12. Nowak MA, RM Anderson, AR McLean, TFW Wolfs, J Goudsmit, RM May (1991). Antigenic diversity thresholds and the development of AIDS. *Science* 254: 963-969.
13. Nowak MA, RM May (1991). Mathematical biology of HIV infections: Antigenic variation and diversity threshold. *Math Biosci* 106: 1-21.
14. Nowak MA, AR McLean (1991). A mathematical model of vaccination against HIV to prevent development of AIDS. *Proc R Soc B* 246: 141-146.

1992

15. McLean AR, MA Nowak (1992). Competition between zidovudine sensitive and resistant strains of HIV. *AIDS* 6: 71-79.
16. McLean AR, MA Nowak (1992). Models of interactions between HIV and other pathogens. *J theor Biol* 155: 69-86.
17. Nowak MA (1992). Variability in HIV infections. *J theor Biol* 155: 1-20.
18. Nowak MA (1992). What is a quasispecies? *Trends Ecol Evol* 7: 118-121.
19. Nowak MA, RM May (1992). Coexistence and competition in HIV infections. *J theor Biol* 159: 329-342.
20. Nowak MA, RM May (1992). Evolutionary games and spatial chaos. *Nature* 359: 826-829.
21. Nowak MA, K Sigmund (1992). Tit for tat in heterogeneous populations. *Nature* 355: 250-253.
22. Nowak MA, K Tarczy-Hornoch, JM Austyn (1992). The optimal number of major histocompatibility complex molecules in an individual. *P Natl Acad Sci USA* 89: 10896-10899
23. Payne RJH, MA Nowak, BS Blumberg (1992). Analysis of a cellular model to account for the natural history of infection by the hepatitis B virus and its role in the development of primary hepatocellular carcinoma. *J theor Biol* 159: 215-240.
24. Sherratt JA, MA Nowak (1992). Oncogenes, anti-oncogenes and the immune response to cancer: A mathematical model. *Proc R Soc B* 248: 261-271.

1993

25. Nowak MA, RM May (1993). AIDS pathogenesis: Mathematical models of HIV and SIV infections. *AIDS* 7: S3-S18.
26. Nowak MA, RM May (1993). The spatial dilemmas of evolution. *Int J Bifurcat Chaos* 3: 35-78.
27. Nowak MA, AR McLean (1993). Mathematical models for the pathogenesis of AIDS. In *Mathematics Applied to Biology and Medicine*, eds. J Demongeot, V Capasso. Winnipeg: Wuerz Publishing, 275-284.
28. Nowak MA, K Sigmund (1993). A strategy of win-stay, lose-shift that outperforms tit-for-tat in the Prisoner's Dilemma game. *Nature* 364: 56-58.

29. Nowak M, K Sigmund (1993). Chaos and the evolution of cooperation. *P Natl Acad Sci USA* 90: 5091-5094.

1994

30. Berry RM, MA Nowak (1994). Defective escape mutants of HIV. *J theor Biol* 171: 387-395.
31. Bonhoeffer S, MA Nowak (1994). Intra-host versus inter-host selection: Viral strategies of immune function impairment. *P Natl Acad Sci USA* 91: 8062-8066.
32. Bonhoeffer S, MA Nowak (1994). Mutation and the evolution of virulence. *Proc R Soc B* 258: 133-140.
33. May RM, MA Nowak (1994). Superinfection, metapopulation dynamics, and the evolution of diversity. *J theor Biol* 170: 95-114.
34. Moxon ER, PB Rainey, MA Nowak, RE Lenski (1994). Adaptive evolution of highly mutable loci in pathogenic bacteria. *Curr Biol* 4: 24-33.
35. Nowak MA (1994). The evolutionary dynamics of HIV infections. In *First European Congress of Mathematics: Paris, July 6-10, 1992, Vol. II*, eds. A Joseph, F Mignot, F Murat, B Prum, R Rentschler. Basel: Birkhauser, 311-326.
36. Nowak MA, S Bonhoeffer, RM May (1994). More spatial games. *Int J Bifurcat Chaos* 4: 33-56.
37. Nowak MA, S Bonhoeffer, RM May (1994). Spatial games and the maintenance of cooperation. *P Natl Acad Sci USA* 91: 4877-4881.
38. Nowak MA, RM May (1994). Superinfection and the evolution of parasite virulence. *Proc R Soc B* 255: 81-89.
39. Nowak MA, K Sigmund (1994). The alternating Prisoner's Dilemma. *J theor Biol* 168: 219-226.
40. Payne RJH, MA Nowak, BS Blumberg (1994). A cellular model to explain the pathogenesis of infection by the hepatitis B virus. *Math Biosci* 123: 25-58.
41. Tilman D, RM May, CL Lehman, MA Nowak (1994). Habitat destruction and the extinction debt. *Nature* 371: 65-66.

1995

42. Bonhoeffer S, EC Holmes, MA Nowak (1995). Causes of HIV diversity. *Nature* 376: 125.
43. Bonhoeffer S, EC Holmes, MA Nowak (1995). Varying selection pressures in HIV -1 infection. *J Acq Immun Def Synd* 10: 85.
44. Bonhoeffer S, MA Nowak (1995). Can live attenuated virus work as post-exposure treatment? *Immunol Today* 16: 131-135.
45. Lipsitch M, EA Herre, MA Nowak (1995). Host population structure and the evolution of virulence: A "law of diminishing returns." *Evolution* 49: 743-748.
46. Lipsitch M, MA Nowak (1995). The evolution of virulence in sexually transmitted HIV/AIDS. *J theor Biol* 174: 427-440.
47. Lipsitch M, MA Nowak, D Ebert, RM May (1995). The population dynamics of vertically and horizontally transmitted parasites. *Proc R Soc B* 260: 321-327.
48. May RM, S Bonhoeffer, MA Nowak (1995). Spatial games and evolution of cooperation. In *Advances in Artificial Life: Third European Conference on Artificial Life, Granada, Spain, June 4-6, 1995*, eds. F Moran, A Moreno, JJ Merelo, P Chacon. Berlin: Springer, 749-759.

49. May RM, MA Nowak (1995). Coinfection and the evolution of parasite virulence. *Proc R Soc B* 261: 209-215.
50. McMichael AJ, S Rowland-Jones, P Klenerman, et al (1995). Epitope variation and t-cell recognition. *J Cell Biochem Suppl S21A*: 60.
51. Nowak MA (1995). AIDS pathogenesis: From models to viral dynamics in patients. *J Acq Immun Def Syn* 10: S1-S5.
52. Nowak M (1995). Evolutionary dynamics of HIV infections. In *Models for Infectious Human Diseases: Their Structure and Relation to Data*, eds. V Isham, G Medley. Cambridge: Cambridge University Press.
53. Nowak MA, S Bonhoeffer, C Loveday, P Balfe, M Semple, S Kaye, M Tenant-Flowers, R Tedder (1995). HIV results in the frame: Results confirmed. *Nature* 375: 193.
54. Nowak MA, RM May, RE Phillips, S Rowland-Jones, DG Lalloo, S McAdam, P Klenerman, B Köppe, K Sigmund, CRM Bangham, AJ McMichael (1995). Antigenic oscillations and shifting immunodominance in HIV-1 infections. *Nature* 375: 606-611
55. Nowak MA, RM May, K Sigmund (1995). Immune responses against multiple epitopes. *J theor Biol* 175: 325-353.
56. Nowak M A, RM May, K Sigmund (1995). The arithmetics of mutual help. *Sci Am* 272: 76-81.
57. Nowak MA, AJ McMichael (1995). How HIV defeats the immune system. *Sci Am* 273: 58-65.
58. Nowak MA, K Sigmund (1995). Invasion dynamics of the finitely repeated Prisoner's Dilemma. *Game Econ Behav* 11: 364-390.
59. Nowak MA, K Sigmund, E El-Sedy (1995). Automata, repeated games and noise. *J Math Biol* 33: 703-722.
60. Wei X, SK Ghosh, ME Taylor, VA Johnson, EA Emini, P Deutsch, JD Lifson, S Bonhoeffer, MA Nowak, BH Hahn, MS Saag, GM Shaw (1995). Viral dynamics in human immunodeficiency virus type 1 infection. *Nature* 373: 117-122.

1996

61. Antia R, MA Nowak, RM Anderson (1996). Antigenic variation and the within-host dynamics of parasites. *P Natl Acad Sci USA*. 93: 985-989.
62. Boerlijst MC, S Bonhoeffer, MA Nowak (1996). Viral quasi-species and recombination. *Proc R Soc B* 263: 1577-1584.
63. Bonhoeffer S, AVM Herz, MC Boerlijst, S Nee, MA Nowak, RM May (1996). Explaining "linguistic features" of noncoding DNA. *Science* 271: 14-15.
64. Bonhoeffer S, AVM Herz, MC Boerlijst, S Nee, MA Nowak, RM May (1996). No signs of hidden language in noncoding DNA. *Phys Rev Lett* 76: 1977.
65. Herz AVM, S Bonhoeffer, RM Anderson, RM May, MA Nowak (1996). Viral dynamics in vivo: Limitations on estimates of intracellular delay and virus decay. *P Natl Acad Sci USA* 93: 7247-7251.
66. Klenerman P, RE Phillips, CR Rinaldo, LM Wahl, G Ogg, RM May, AJ McMichael, MA Nowak (1996). Cytotoxic T lymphocytes and viral turnover in HIV type 1 infection. *P Natl Acad Sci USA* 93: 15323-15328.
67. Lipsitch M, S Siller, MA Nowak (1996). The evolution of virulence in pathogens with vertical and

horizontal transmission. *Evolution* 50: 1729-1741.

68. McMichael AJ, P Goulder, S Rowland-Jones, MA Nowak, R Philips (1996). HIV escapes from cytotoxic lymphocytes. *Immunology* 89: 111.
69. Nowak MA (1996). Immune responses against multiple epitopes: A theory for immunodominance and antigenic variation. *Semin Virol* 7: 83-92.
70. Nowak MA, RM Anderson, MC Boerlijst, S Bonhoeffer, RM May, AJ McMichael (1996). HIV-1 evolution and disease progression. *Science* 274: 1008-1011.
71. Nowak MA, CRM Bangham (1996). Population dynamics of immune responses to persistent viruses. *Science* 272: 74-79.
72. Nowak MA, S Bonhoeffer, AM Hill, R Boehme, HC Thomas, H McDade (1996). Viral dynamics in hepatitis B virus infection. *P Natl Acad Sci USA* 93: 4398-4402.
73. Nowak MA, S Bonhoeffer, RM May (1996). Reply to Robustness of cooperation, A Mukherji, V Rajan, J Slagle. *Nature* 379: 126.
74. Payne RJH, MA Nowak, BS Blumberg (1996). The dynamics of hepatitis B virus infection. *P Natl Acad Sci USA* 93: 6542-6546.
75. Stekel DJ, MA Nowak, TRE Southwood (1996). Prediction of future BSE spread. *Nature* 381: 119.
76. Tilman D, C Lehman, R May, M Nowak (1996). Reply to Species fragmentation or area loss? S Budiansky. *Nature* 382: 216.

1997

77. Bittner B, S Bonhoeffer, MA Nowak (1997). Virus load and antigenic diversity. *B Math Biol* 59: 881-896.
78. Boerlijst MC, MA Nowak, K Sigmund (1997). Equal pay for all prisoners. *Am Math Mon* 104: 303-305.
79. Boerlijst MC, MA Nowak, K Sigmund (1997). The logic of contrition. *J theor Biol* 185: 281-293.
80. Bonhoeffer S, JM Coffin, MA Nowak (1997). Human immunodeficiency virus drug therapy and virus load. *J Virol* 71: 3275-3278.
81. Bonhoeffer S, RM May, GM Shaw, MA Nowak (1997). Virus dynamics and drug therapy. *P Natl Acad Sci USA* 94: 6971-6976.
82. Bonhoeffer S, MA Nowak (1997). Pre-existence and emergence of drug resistance in HIV-1 infection. *Proc R Soc B* 264: 631-637.
83. Chun T-W, L Stuyver, SB Mizell, LA Ehler, JAM Mican, M Baseler, AL Lloyd, MA Nowak, AS Fauci (1997). Presence of an inducible HIV-1 latent reservoir during highly active antiretroviral therapy. *P Natl Acad Sci USA* 94: 13193-13197.
84. Cooke J, MA Nowak, MC Boerlijst, J Maynard-Smith (1997). Evolutionary origins and maintenance of redundant gene expression during metazoan development. *Trends Genet* 13: 360-364.
85. Goulder PJR, RE Phillips, RA Colbert, S McAdam, G Ogg, MA Nowak, P Giangrande, G Luzzi, B Morgan, A Edwards, AJ McMichael, S Rowland-Jones (1997) Late escape from an immunodominant cytotoxic T-lymphocyte response associated with progression to AIDS. *Nat Med* 3: 212-217.
86. Goulder P, D Price, M Nowak, S Rowland-Jones, R Phillips, A McMichael (1997). Co-evolution of

- human immunodeficiency virus and cytotoxic T-lymphocyte responses. *Immunol Rev* 159: 17-29.
87. Lifson JD, MA Nowak, S Goldstein, JL Rossio, A Kinter, G Vasquez, TA Wilttrout, C Brown, D Schneider, L Wahl, AL Lloyd, J Williams, WR Elkins, AS Fauci, VM Hirsch (1997). The extent of early viral replication is a critical determinant of the natural history of simian immunodeficiency virus infection. *J Virol* 71: 9508-9514.
 88. May RM, DJ Stekel, MA Nowak (1997). Antigenic diversity thresholds and hazard functions. *Math Biosci* 139: 59-68.
 89. Nowak MA, MC Boerlijst, J Cooke, J Maynard Smith (1997). Evolution of genetic redundancy. *Nature* 388: 167-171.
 90. Nowak MA, S Bonhoeffer, GM Shaw, RM May (1997). Anti-viral drug treatment: Dynamics of resistance in free virus and infected cell populations. *J theor Biol* 184: 203-217.
 91. Nowak MA, AL Lloyd, GM Vasquez, TA Wilttrout, LM Wahl, N Bischofberger, J Williams, A Kinter, AS Fauci, VM Hirsch, JD Lifson (1997). Viral dynamics of primary viremia and antiretroviral therapy in simian immunodeficiency virus infection. *J Virol* 71: 7518-7525.
 92. Sigmund K, Nowak M A (1997) The natural history of mutual aid: An eye for an eye, and a meal for a meal. In *Wissenschaft als Kultur*, ed. F Stadler. New York: Springer, 259-272.
 93. Stekel D, CE Parker, MA Nowak (1997). A model of lymphocyte recirculation. *Immunol Today* 18: 216-221.
 94. Wein LM, SA Zenios, MA Nowak (1997). Dynamic multidrug therapies for HIV: A control theoretic approach. *J theor Biol* 185: 15-29.
- 1998**
95. Goh WC, ME Rogel, CM Kinsey, SF Michael, PN Fultz, MA Nowak, BH Hahn, M Emerman (1998). HIV-1 Vpr increases viral expression by manipulation of the cell cycle: A mechanism for selection of Vpr in vivo. *Nat Med* 4: 65-71.
 96. Kilby JM, S Hopkins, TM Venetta, B DiMassimo, GA Cloud, JY Lee, L Alldredge, E Hunter, D Lambert, D Bolognesi, T Matthews, MR Johnson, MA Nowak, GM Shaw, MS Saag (1998). Potent suppression of HIV-1 replication in humans by T-20, a peptide inhibitor of gp41-mediated virus entry. *Nat Med* 4: 1302-1307.
 97. Levin BR, R Antia, E Berliner, P Bloland, S Bonhoeffer, M Cohen, T DeRouin, PI Fields, H Jafari, D Jernigan, M Lipsitch, JE McGowan, P Mead, M Nowak, T Porco, P Sykora, L Simonsen, J Spitznagel, R Tauxe, F Tenover (1998). Resistance to antimicrobial chemotherapy: A prescription for research and action. *Am J Med Sci* 315: 87-94.
 98. Nowak MA, DC Krakauer, A Klug, RM May (1998). Prion infection dynamics. *Integr Biol* 1: 3-15.
 99. Nowak MA, K Sigmund (1998). Darwins Dynamik. *DMV-Mitteilungen* 4: 37-44.
 100. Nowak MA, K Sigmund (1998). Evolution of indirect reciprocity by image scoring. *Nature* 393: 573-577.
 101. Nowak MA, K Sigmund (1998). The dynamics of indirect reciprocity. *J theor Biol* 194: 561-574.
 102. Nowak MA, K Sigmund (1998). What two legs can learn from four legs. Book review of *Foundations of Social Evolution*, SA Frank; *Cooperation Among Animals*, AL Dugatkin. *Nature* 395: 760-761.
 103. Ogg GS, X Jin, S Bonhoeffer, PR Dunbar, MA Nowak, S Monard, JP Segal, Y Cao, SL Rowland-

- Jones, V Cerundolo, A Hurley, M Markowitz, DD Ho, DF Nixon, AJ McMichael (1998). Quantitation of HIV-1-specific cytotoxic T lymphocytes and plasma load of viral RNA. *Science* 279: 2103-2106.
104. Ostrowski MA, DC Krakauer, Y Li, SJ Justement, G Learn, LA Ehler, SK Stanley, M Nowak, AS Fauci (1998). Effect of immune activation on the dynamics of human immunodeficiency virus replication and on the distribution of viral quasispecies. *J Virol* 72: 7772-7784.
105. Regoes RR, D Wodarz, MA Nowak (1998). Virus dynamics: The effect of target cell limitation and immune responses on virus evolution. *J theor Biol* 191: 451-462.
106. Ribeiro RM, S Bonhoeffer, MA Nowak (1998). The frequency of resistant mutant virus before anti-viral therapy. *AIDS* 12: 461-465.
107. Sigmund K, M Boerlijst, MA Nowak (1998). Automata and inner states for repeated games. In *Game Theory, Experience, Rationality*, ed. W Leinfeller, E Köhler. London: Kluwer Academic Publishers, 131-139.
108. Sigmund K, MA Nowak (1998). Cyber-sociology. Book review of *The Complexity of Cooperation: Agent-Based Models of Competition and Collaboration*, R Axelrod. *Nature* 392: 457.
109. Wodarz D, P Klenerman, MA Nowak (1998). Dynamics of cytotoxic T-lymphocyte exhaustion. *Proc R Soc B* 265: 191-203.
110. Wodarz D, MA Nowak (1998). Mathematical models of virus dynamics and resistance. *J HIV Ther* 3: 36-41.
111. Wodarz D, MA Nowak (1998). The effect of different immune responses on the evolution of virulent CXCR4-tropic HIV. *Proc R Soc B* 265: 2149-2158.
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