The History of Simulation in Industrial Engineering

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Outline

Overall Theme of the Talk

Many of the significant advances in the theory and practice of simulation over the past one hundred years have been driven by problems central to industrial engineering and the systems analysis techniques developed to solve them.

In this talk we highlight some of these advances and how industrial engineering and simulation have coevolved.

Role of Simulation in the Discovery of Student's t-Distribution

William Sealy Gosset, trained in mathematics and chemistry, became a brewer with Arthur Guiness, Son & Co. Ltd., in 1899 at the age of 23.

Gosset's research on the selection, cultivation, and treatment of barley and hops revealed the following key characteristics of the brewing process:

- variability of materials;
- susceptibility to temperature changes; and
- the need to run short series of experiments.

Role of Simulation in the Discovery of Student's t-Distribution (Cont'd)

Gosset was faced with the problem of maintaining consistent quality of Guiness's ale and stout based on data with the following drawbacks:

- small sample sizes; and
- measurements that are not independent.

Thus he was working in quality control 25 years before the Shewhart chart.

Gosset arranged to spend 1906 studying under Karl Pearson at University College London, but he quickly discovered that Pearson's large-sample statistical methods were inadequate for Guiness's problems.

Gosset's Approach to Small-Sample Process Control

To estimate the mean μ of a normal population based on a random sample $\{X_i : i = 1, \ldots, n\}$ with sample size n in the range $4 \le n \le 10$, he proceeded as follows:

a. He calculated the sample mean and variance,

$$\bar{X} = \frac{1}{n}\sum_{i=1}^{n} X_i \quad \text{and} \quad S^2 = \frac{1}{n}\sum_{i=1}^{n}\left(X_i - \bar{X}\right)^2. \tag{1}$$

b. He derived the mean, variance, skewness, and kurtosis of S^2, and he showed that these characteristics of S^2 exactly match those of a Pearson type III curve; then he ***guessed*** that S^2 has this distribution when the $\{X_i\}$ are normal.

Gosset's Approach to Small-Sample Process Control (Cont'd)

c. He showed that if the $\{X_i\}$ are sampled from a symmetric distribution, then

- the statistics $\bar{X}$ and S are uncorrelated; and
- the statistics $\bar{X}^2$ and S^2 are also uncorrelated.

d. Since the normal distrbution is symmetric about its mean, Gosset ***guessed*** that in random samples from a normal distribution, $\bar{X}$ and S^2 must be independent.

Gosset's Approach to Small-Sample Process Control (Cont'd)

Gosset used his results **a–d** to show that the probability density function of the ratio

$$Z = \frac{\bar{X} - \mu}{S} \tag{2}$$

based on a random sample of size n from a normal distribution with mean μ has the form

$$f(z) \propto \frac{1}{\left(1 + z^2\right)^{n/2}}\,; \tag{3}$$

and from (3), he computed tables of selected percentile points of the distribution of Z for sample sizes in the range $4 \leq n \leq 10$.

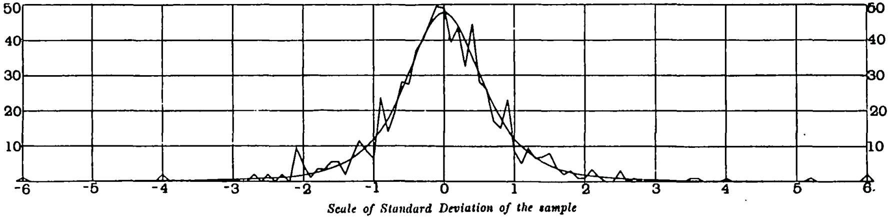
Gosset's Approach to Small-Sample Process Control (Cont'd)

To validate his results, Gosset conducted a precomputer simulation experiment by randomly sampling from a population of left middle finger lengths of 3,000 habitual British criminals obtained from New Scotland Yard.

- These measurements were written on 3,000 pieces of cardboard, thoroughly shuffled, and drawn at random to yield a randomly ordered list of the entre population.
- Each consecutive set of 4 measurements from this list was taken as a sample of size $n = 4$, so that there were 750 such samples.

- For each sample of size 4, Equations (1)–(2) were used to compute the corresponding Z statistic; and a histogram of the resulting 750 Z-values was superimposed on the density (3) with $n = 4$ as shown below.

DIAGRAM IV. Comparison of the theoretical frequency curve $y = \frac{1500}{\pi}\left(1+\frac{x^2}{s^2}\right)^{-2}$, with an actual sample of 750 cases.



- Guiness allowed Gosset to publish his results, provided he used a pseudonym and no proprietary data was used. These results were published under the pseudonym “Student” in 1908.

VOLUME VI MARCH, 1908 No. 1

BIOMETRIKA.

THE PROBABLE ERROR OF A MEAN.

BY STUDENT.

Introduction.

ANY experiment may be regarded as forming an individual of a "population" of experiments which might be performed under the same conditions. A series of experiments is a sample drawn from this population.

Postscript on the Discovery of Student's t-Distribution

- R. A. Fisher finally published a mathematically rigorous derviation of Student's t-Distribution in 1921.
- This inaugural application of simulation to industrial process control is a remarkable example of the synergy of simulation-based experimentation and analytic techniques in the discovery of the exact solution of what is arguably a classical industrial-engineering problem.

K. D. Tocher and the General Simulation Program (GSP)

Keith Douglas Tocher worked in the UK Ministry of Aircraft Production (1942–1945), National Physical Laboratories (1945–1948), and at Imperial College London (1948–1957) before he joined the United Steel Companies in 1957 as a research applications manager. He held positions in the British steel industry until 1980, when he became a professor of operational research at the University of Southampton.

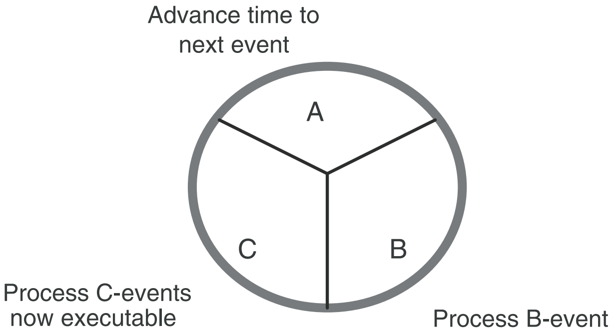
K. D. Tocher and the General Simulation Program (GSP) (Cont'd)

Tocher developed the General Simulation Program (GSP), the first general-purpose simulator, as a tool for ***automatically*** building a simulation of an industrial plant that comprises a set of machines, each cycling through states such as busy, idle, unavailable, and failed. The machine states and the times of the next machine actions collectively define the state of the plant; see

> Tocher, K. D., and D. G. Owen. 1960. The automatic programming of simulations. In *Proceedings of the Second International Conference on Operational Research*, ed. J. Banbury and J. Maitland, 50–68. London: The English Universities Press Ltd.

Tocher’s Three-Phase Activity-Scanning Method for Timing Control

The state of each machine evolves over time in three phases: (A) advancing time to the next scheduled event that is “bound to occur” and that may change the machine’s state (this is called a “B-event”); (B) processing the associated B-event; and (C) processing “conditional” events (called “C-events”) that are not scheduled for specific times but are instead subject to prespecified conditions on machine state.



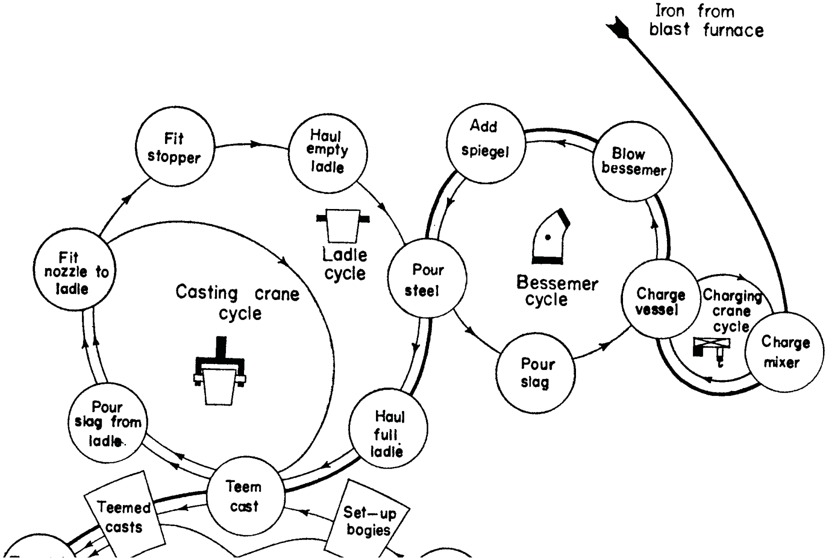
Tocher's Three-Phase Activity-Scanning Method for Timing Control

The B-events are strictly based on ***time***, and the C-events, on ***state***.

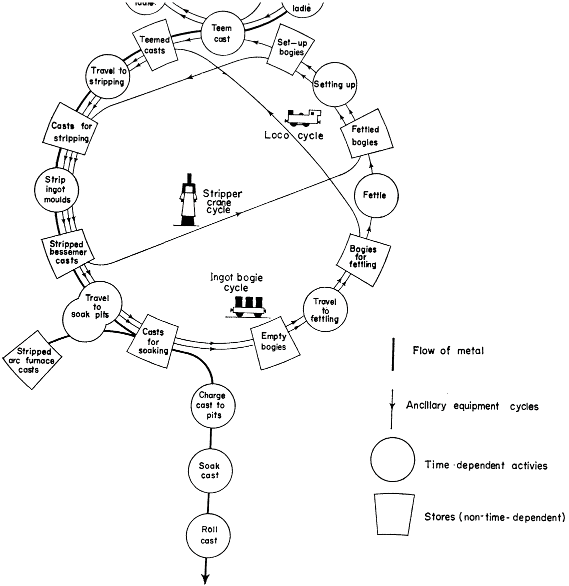
Repeated scans of the C-events occur until time must be advanced for the next event to occur.

The characterization of the time and state interaction to produce events is the crucial requirement of all modeling languages used in discrete event simulation.

Activity Cycle Diagram of Steelmaking Process



Activity Cycle Diagram of Steelmaking Process (Cont'd)



The Central Problems of Digital Simulation

Based on their extensive research and practical experience involving manufacturing simulations in the 1950s and early 1960s, R. W. Conway, B. M. Johnson, and W. L. Maxwell of Cornell University laid out the central problems of digital simulation in two seminal papers:

- Conway, R. W., B. M. Johnson, and W. L. Maxwell. 1959. Some problems of digital systems simulation. *Management Science* 6 (1): 92–110.
- Conway, R. W. 1963. Some tactical problems in digital simulation. *Management Science* 10 (1): 47–61.

Conway, Johnson, and Maxwell said that computer simulation problems fall into two broad categories—the ***construction*** of the simulation, and the ***use*** of the simulation.

The Central Problems of Digital Simulation (Cont'd)

The problems of simulation model construction include:

- Modular design of simulation programs for easy revision;
- Management of computer memory;
- Control of error arising from the discretization of all continuous quantities that is inherent in digital simulation;
- Design and implementation of an efficient time-advance mechanism; and
- Management of files containing the simulation's entities.

Although many of the above problems have been largely resolved, the design and implementation of an efficient time-advance procedure for handling Tocher's B- and C-events is still an active area of research and development.

The Central Problems of Digital Simulation (Cont'd)

The main problems in using simulation include the ***strategic*** problem of designing a simulation experiment and the following ***tactical*** problems on how to run the simulations specified in the experimental design:

a. Determining when a simulation is in equilibrium (steady state) so that any transients caused by the simulation's initial condition have died out;

b. Estimating the precision (variance) of simulation-based estimators of steady-state performance; and

c. Performing precise comparisons of alternative system simulations.

The Central Problems of Digital Simulation (Cont'd)

For the start-up problem **a**, Conway (1963) proposed the first widely used rule for truncating (deleting) simulation-generated observations that are contaminated by initialization bias.

For the variance-estimation problem **b**, Conway (1963) proposed the method of batch means, which is still widely used in practice and is the basis for much ongoing research.

For the comparison problem **c**, Conway (1963) rejected ANOVA and proposed the use of statistical ranking-and-selection procedures, which are now widely used in practice and are the basis for much ongoing research.

Manufacturing Systems: An Application Driver

While the work of Conway and others attacked fundamental issues in the general use of simulation, concurrent attempts to solve major problems in manufacturing were drawing increasing attention.

In his 1958 Ph.D. dissertation at UCLA, Alan Rowe conceived of using simulation to investigate scheduling rules in the job-shop environment.

Drawing on Rowe's experience, Harry Markowitz and Mort Allen developed the General Electric Manufacturing Simulator (GEMS). Lessons learned by Markowitz were helpful in his later developments of SIMSCRIPT (described later).

Manufacturing Systems: An Application Driver (Cont'd)

During the period 1960–1962, John Colley, Harold Steinhoff, and others developed a model of Hughes Aircraft's El Segundo fabrication plant based on the IBM Job Shop Scheduler (JSS).

This simulation was used to test dispatching rules using operational data, and the results were used in "near-real-time" mode to guide production decisions in the ensuing shift; see

- Bulkin, M. H., J. L. Colley, and H. W. Steinhoff, Jr. 1966. Load forecasting, priority sequencing, and simulation in a job shop control system. *Management Science* 13 (1): B29–B51.

Manufacturing Systems: An Application Driver (Cont'd)

Donald G. Malcolm chaired two symposia on the potential impact of simulation on industrial engineering; see

- Malcolm, D. G. 1958. Systems simulation—A fundamental tool for industrial engineering. *Journal of Industrial Engineering* May–June: 177–187.

Geoffrey Gordon and the General Purpose Simulation System (GPSS)

Geoffrey Gordon joined the Advanced Systems Development Division of IBM in 1960 as Manager of Simulation Development; and during the period 1960–1961, he introduced the General Purpose System Simulator, which was later renamed the General Purpose Simulation System (GPSS).

GPSS was designed to facilitate rapid simulation modeling of complex teleprocessing systems involving, for example, urban traffic control, telephone call interception and switching, airline reservation processing, and steel-mill operations.

Geoffrey Gordon and the General Purpose Simulation System (GPSS) (Cont'd

GPSS exploits the ***process-interaction approach*** to simulation, whereby we model the sequence of activities in which temporary entities (transactions) engage permanent entities using resources in moving through the system or waiting for the release of resources because of competition (interaction) with other entities for the resources required to complete the production process.

GPSS is notable for its effective use of specialized block diagrams for graphically representing the flow of entities through the system.

The Enduring Legacy of Geoffrey Gordon and GPSS

Because of its remarkable ease of use and the marketing efforts of IBM, GPSS was distinguished as the most popular simulation language of its time—and the process-interaction approach to simulation is still the method of choice for many large-scale simulations of complex industrial operations.

The 1967 forerunner of the Winter Simulation Conference (WSC) was the Conference on Applications of Simulation Using the General Purpose Simulation System (GPSS), which in subsequent years was expanded to include papers on any simulation language or any aspect of simulation applications.

WSC is now the premier international forum for disseminating recent advances in the field of system simulation.

Dahl and Nygaard's Development of SIMULA

Ole-Johan Dahl and Kristen Nygaard worked for the Norwegian Defense Research Establishment as operations research analysts from the late 1940s to the early 1960s, when they both moved to the Norwegian Computer Center.

During the period 1961–1967, Dahl and Nygaard coinvented object-oriented programming through their development of the general-purpose programming languages SIMULA I and SIMULA 67, which include special features designed to facilitate the description, interaction, suspension, and reactivation of processes.

Dahl and Nygaard's Development of SIMULA

SIMULA has been not only one of the most influential simulation languages but also the programming language with the most pronounced effect on the development of software engineering.

The introduction of SIMULA led to a fundamental change in the techniques for designing and programming software systems, resulting in applications code that is reliable, scalable, and reusable.

Markowitz, Hausner, and Karr's Development of SIMSCRIPT

In the 1950s, Harry Markowitz (who later received the Nobel Prize in Economics) did pioneering work along with Richard Conway and others on the development of the General Electric Manufacturing Simulator (GEMS), which was a predecessor of SIMSCRIPT.

While working at the RAND Corporation in the early 1960s, Harry Markowitz, Bernard Hauser, and Richard Karr developed SIMSCRIPT as a generalization of the machine and job-shop simulators that preceded it.

Markowitz, Hausner, and Karr's Development of SIMSCRIPT (Cont'd)

SIMSCRIPT is distinguished by the following key features:

- ***Temporary entities*** are created and destroyed during the simulation;
- ***Permanent entities*** are available throughout the simulation;
- ***Attributes*** are numerical characteristics specific to each individual entity; and
- ***Sets*** define classes of permanent entities, with ownership and membership functions defining the relationships among these entities.

Kiviat, Pritsker, & the General Activity Simulation Program (GASP)

Trained as an industrial engineer at Cornell University, Philip J. Kiviat developed GASP in 1961 while working in the Applied Research Laboratory of United States Steel. In the mid-1960s, Kiviat moved to the RAND Corporation and led the design and development of SIMSCRIPT II.

In 1967, Alan Pritsker (Arizona State University) collaborated with Kiviat on the develoment of GASP II, which achieved widespread use in the industrial engineering community in the late 1960s and early 1970s. Pritsker was motivated by the need for a simulation capability within the limitations of an IBM 1130.

Kiviat, Pritsker, & the General Activity Simulation Program (GASP) (Cont'd)

As in GPSS, flowcharts are used in GASP for specifying the events that define changes in system status; but whereas GPSS uses its own special-purpose flowchart symbols, GASP uses general-purpose flowcharting symbols.

As in SIMSCRIPT, GASP uses an event-oriented approach with entities and attributes; but GASP has only temporary entities that can be inserted into and removed from files.

Enhanced Modeling Tools

- Pritkser and Hurst's development of GASP IV
- Kiviat, Villanueva, and Markowitz's development of SIMSCRIPT II.5
- Pritsker and Pegden's development of SLAM
- Pegden's Development of SIMAN
- Nance's Conical Methodology for Object-Oriented Model Development
- Schruben's Event Graphs
- Development of specialty simulation products for niche markets
- Sargent's contributions to formal verification and validation

Contributions to Variate Generation

Big Question: How to generate proper random variates quickly and efficiently?

- Fishman's text: Succinct categorization of a number of useful techniques
- Devroye's text: Major compendium of all techniques to date
- Schmeiser's work: Fundamental contributions to development of algorithms for univariate and multivariate random variates; easy-to-read survey
  - Poisson, gamma, etc.
  - M/M/1 waiting-time process
- Beautiful tricks
  - Ahrens–Dieter normal generator
  - Various nonparametric generators

Contributions to Output Analysis

Big Question: How to analyze resulting output of complicated systems?

Big Problem: Simulation output is almost never independent, identically distributed, or normal

- Schmeiser formalizes the properties of the batch means method
- Fishman formulates a time-series approach to output analysis
- Fishman and Iglehart formulate the regenerative method
- Schmeiser formulates the method of overlapping batch means
- Schruben formulates the method of standardized time series
- Wilson and Pritsker deal with initialization bias
- Several authors work on ranking-and-selection and optimization problems

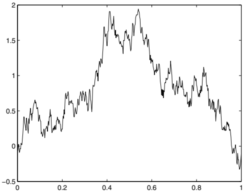
Proliferation of Simulation Languages with Enhanced Graphics

Goal: Make simulation languages more powerful and easy to use

- Traditional discrete-event simulation languages incorporate animation / graphics
  - SIMAN evolves into Arena
  - GPSS/H incorporates Proof Animation
- Continued development / use of other graphics-based languages
  - ProModel / MedModel
  - AutoMod (3-D capabilities)
  - Many others
- Numerous free simulation packages, some of which have graphics capabilities
  - Simkit (Java-based)
  - D-SOL (Java-based, with graphics)
  - Many others
- Simulation now in everyday use in a variety of IE applications areas

Exciting Research Developments

- Fishman's Contributions to Monte Carlo Analysis
- Glasserman's Contibutions to Financial Modeling

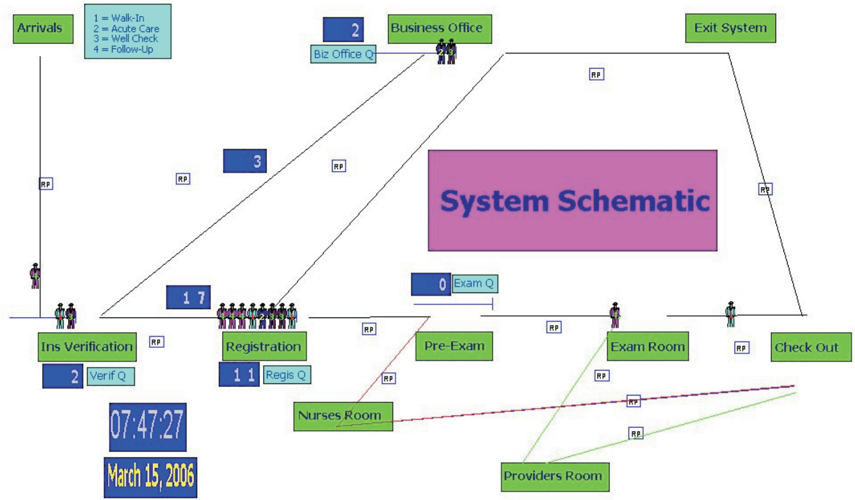


- Explosion in Simulation Optimization Research
- Statistical Applications
  - Monte Carlo Markov Chain Techniques
  - Ranking and Selection Methods
  - Sophisticated Distribution and Process Modeling Schemes (e.g., Wilson et al.)
  - Advanced Output Analysis Methods
- Large-Scale Pandemic Influenza Propagation Models

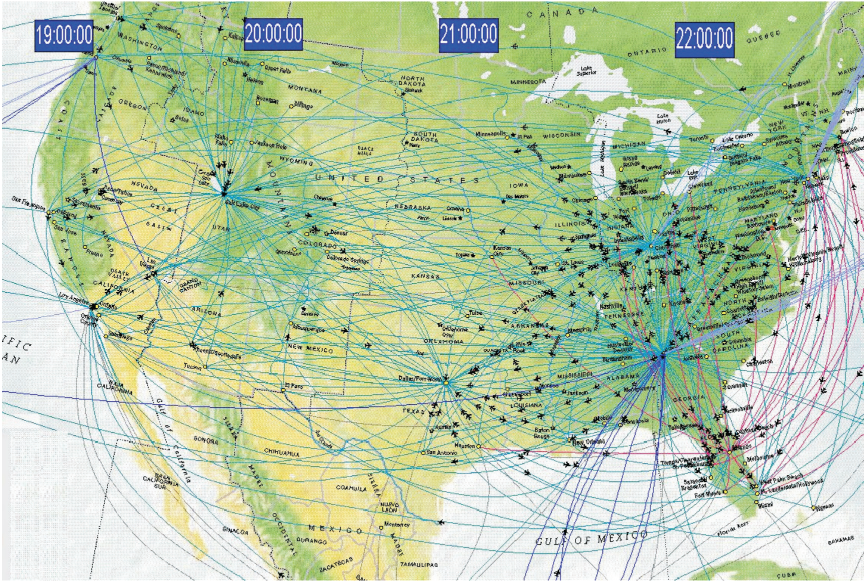
Simulation in Everyday Life

- Numerous excellent textbooks on the market at all levels. For example,
  - Banks, Carson, Nelson, and Nicol; Kelton, Sadowski, and Sturrock; Rossetti
  - Law (and Kelton); Fishman (various)
  - Asmussen and Glynn
- Many highly regarded conferences in which simulation plays a major role
  - Winter Simulation Conference (IIE is a co-sponsor)
  - Summer Simulation Conference
  - IERC, INFORMS
  - ...
- Wide range of applications
  - Service industries (e.g., hospital patient-flow modeling)
  - Maufacturing
  - Military
  - Airline industry
  - Healthcare applications

Simulation is Widely Used in Healthcare



Simulation in the Airline Industry



What Is the Point of All This?

Some general observations on the advantages of the industrial engineering perspective.

- Many of the significant advances in the theory and practice of system simulation over the past one hundred years have been driven by researchers and practitioners working as industrial engineers.
- The overall systems perspective of industrial engineering seems to be the key to this phenomenon.

The Last Word

The Increasingly Critical Role of Industrial Engineering and Simulation

As the economic, social, and environmental problems confronting all mankind become increasingly critical and interrelated, industrial engineers have an extraordinary opportunity to take the lead in synthesizing effective solutions that draw on all areas of specialized technical knowledge—and the sheer complexity of these problems dictates that system simulation will be an essential tool for crafting good solutions.

The primary case in point: for his work as chair of the Intergovernmental Panel on Climate Change, Rajendra Pachauri (Ph.D., Industrial Engineering and Economics, North Carolina State University, 1974) shared the 2007 Nobel Peace Prize with Al Gore.