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Activity Completion Times in PERT and Scheduling Network Simulation, Part II

By Dr. Eva Regnier

The risk of failing to complete activities and entire projects on time and the resulting cost overruns are critical elements of project management. This is the second of a two-part series on project management tools used to model and measure uncertainty in scheduling of complex, multi-activity projects.

The first article, which appeared in the January 2005 issue of the DRMI newsletter, focused on project completion times in the Program Evaluation Review Technique (PERT) and network simulation. That article described how key assumptions can bias both PERT and simulation to produce unrealistically optimistic probability distributions for project completion time, even when used correctly.

This article focuses on individual task completion times, examining the probability distribution generally used to model the uncertainty in activity completion times in simulation and in PERT. It also examines the common assumptions used to derive estimates of the parameters required to describe the beta distribution and to derive mean and standard deviation of project completion times in PERT.

The article offers:

- a historical background on PERT;
- an introduction to the beta distribution;
- an explanation of the relationship between the PERT formulas and the beta distribution; and
- Guidelines for selecting parameters for a beta distribution to create the desired shape.

<u>The beta distribution</u>

The PERT method introduces uncertainty into a network by treating each activity's completion

(con't on p.4)

DRMI Activities

International Defense Management Course 05-1

IDMC05-1's 45 participants from 34 countries were off to Washington, DC, March 15-20. In addition to the usual briefings, they were entertained at the Pentagon and State Department on March 17 by a sea of people wearing green, also an addition to the trip was a Sunday visit to Mount Vernon. It was a great opportunity for the faculty to gather some good information and continue to bond with the participants.

Training Program Management Review (TPMR)

DRMI will send representatives to the annual Training Program Management Reviews at the combatant commands. Steve Hurst will attend the PACOM TPMR in Bangkok, Luis Morales the CENTCOM conference in Tampa, Don Bonsper the EUCOM conference in Germany, and Larry Vaughan the SOUTHCOM conference in Miami. The TPMRs serve as an annual forum for the programming of courses for the next two years. DRMI relies heavily on the conferences to explain its offerings and to coordinate the initial details for its mobile courses.

Lithuania MIDMC

by Lt Col Alan Laverson, USAF

The Defense Resources Management Institute (DRMI) conducted an EIMET course in Vilnius, Lithuania, from 18-29 Oct 2004. This two-week mobile course was quite timely because of the current transformation efforts within the Ministry of National Defense (MoND) and because Lithuania officially became a NATO member on 29 Mar 04 (i.e., seven months earlier). The main goal was to share economic and management tools and concepts that support effective and efficient planning, allocation, and budgeting of scarce public resources.

A total of 28 people participated. Participants included military and civilians from the MoND and all services. They were drawn from a wide variety of organizations, including finance & budget, logistics, policy & plans, operations, mobilization, Conscription Service, NATO Dept., and the National Guard.

Guinea MIDMC
by Dr Anke Richter

The Mobile International Defense Management Course, MIDMC 05-3, to Conakry, Guinea February 7-18 2005 was a great success. Thirty-three participants, from 5 countries (Guinea – 19, Senegal – 5, Chad – 4, Gabon – 3, Mauritania – 2) came together in Conakry to attend this two week course. The course was opened by the President of the National Assembly, El Hadj Boubacar Biro Diallo; the Director of the Cabinet of the National Ministry of Defense, Colonel Kandet Toure ; the Head of the General Staff of the Army, General Kerfolla Comaro; and the American Ambassador to Guinea, the Honorable Jackson MacDonald. The opening ceremony was broadcast on national TV.

Class Picture of Guinea MIDMC 05-3, February 7-18, 2005

Participants came from 9 different ministries in addition to the three services (army, navy, air force), ensuring that a wide range of discussion topics, points-of-view, and inter/intra-agency issues were raised during discussion periods. This diversity offered valuable opportunities to open communication among the various departments and enriched the course. Participant participation was outstanding, interacting fully during lectures and discussion periods and frequently staying more than an hour past the official ending time, discussing case studies of particular interest. The closing ceremony was attended by the First Vice-President of Guinea National Assembly, the Honorable Germaine Doualamou; the Director of the Cabinet of the National Ministry of Defense, Colonel Kandet Toure; the Advisor to the Ministry of Security, Mr. Fode Shapo Toure; the Chief of Third Bureau in Charge of Operations and Instruction, Colonel Lamine Keita; the Military Attaché of Senegal (to Guinea), Colonel Abdoulaye Ndao; and the American Ambassador to Guinea - the Honorable Jackson MacDonald. The closing ceremony was also broadcast on national TV.

Presentation of DRMI Commemorative Plaques. Pictured left to right : First Vice-President of Guinea National Assembly - the Honorable Germaine Doualamou; the American Ambassador to Guinea - the Honorable Jackson MacDonald; the Director of the Cabinet of the National Ministry of Defense - Colonel Kandet Toure; DRMI Team Leader - Anke Richter

The course was taught by Dr. Anke Richter – Team Leader, Dr. Francois Melese, Dr. Eva Regnier, Mr. Allan Polley, Mr. Stephen Hurst, and LtCol William Johnson, USMC. Two of the four faculty members each week spoke French - teaching and conducting discussion groups in this language. Interpreters were available for the other faculty members.

El Salvador MIDMC
by Dr Peter Frederiksen

A DRMI team returned to San Salvador, El Salvador and presented the two week Mobile course to 38 participants from 21 February to 4 March, 2005. Team members were Professors Frederiksen and Morris, Associate Professors Webb and Angelis, Senior Lecturer Bonsper and CDR Maher, USN. Nineteen military officers (representing all services) attended together with 19 civilians. Five of the civilians were from the Ministry of Defense and the remaining 14 civilians represented the following government departments: Environment, Legislative Assembly, Interior, Finance, Foreign Relations, and Tourism. This mix of participants created a powerful dynamic for small group discussions. The government of El Salvador has requested an annual course from now on which DRMI is trying to accommodate. We are scheduled to return during the same time slot in 2006.

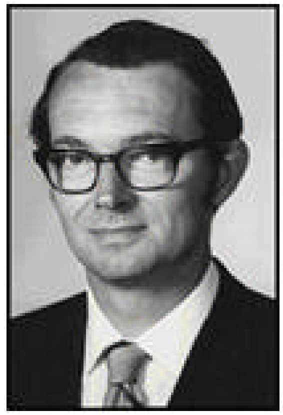
DRMI Policy Guidance Council (PGC)

The annual meeting of the DRMI Policy Guidance Council (PGC) was held at NPS on 24 February. The meeting was chaired by VADM Stanley Szemborski, Principal Deputy Director, OSD Program Analysis and Evaluation. Also in attendance were Mr. Ryan Henry, Principal Deputy Under Secretary of Defense for Policy; Ms. Sharon Cooper, Assistant Director, Defense Human Resources Activity; RADM Patrick Dunne, President, Naval Postgraduate School (NPS) and Director, DRMI; Dr. C.J. LaCivita, Executive Director, DRMI; LTG (Ret) Robert Ord, III, Dean, School of International Graduate Studies, NPS; Ms. Freda Lodge, Director, Policy, Plans, and Programs Directorate, Defense Security Cooperation Agency; CAPT Randall Hendrickson, Military Executive Assistant to the Principal Deputy Under Secretary of Defense for Policy; Mr. John Kreul, Strategist, Office of the Under Secretary of Defense for Policy; and LTC Jeffrey Angers, Operations Research Analyst, Office of the Director, Program Analysis and Evaluation.

Items on the agenda included a review of DRMI curricula and course schedules, a discussion of the processes used to select the countries and students for DRMI courses, a review of best practices in conducting mobile courses, a review of DRMI facilities, a discussion on improving the publicizing of DRMI courses within the DoD, and a discussion of the relationship and synergies of DRMI with the Defense Resources Management Studies program (DRMS).

The Council validated DRMI curricula and processes, agreed to help publicize DRMI courses and decided that it would assume oversight responsibilities for the DRMS program. The intent is to strengthen the relationship between DRMI and the DRMS program, taking advantage of synergies to develop a more efficient and effective educational program.
Overall, it was a very good meeting as the Council expressed its enthusiastic support for DRMI and its programs.

Farewell




The pictures represent change. On the left is the faculty photo of Dr. Robert Boynton when he came to work at DRMI (then named the Navy Management Systems Center) in mid-1970. The right-hand photo is from the recent faculty photo when Bob retired at the end of 2004, after about 34 years of teaching and research at the Naval Postgraduate School.

Bob's research included looking at human resource and management issues, including a NAVAIR-sponsored look into the use of engineering and technical representatives who provide maintenance expertise to young sailors and marines that they need but have not had time or experience to develop. Bob also was called upon to examine the functions and organization of the Air Force air logistic centers. In addition to government-sponsored research he has published in areas such as problem-finding, evaluation of human resource departments, management theory and policy views of managers, and the development of human resource impact statements.

Bob very much appreciated the opportunity to see the world and meet its people. The Institute initially responded to requests from other nations for two-week short courses on resource management. When DOD decided we should only do U.S. courses it provided the opportunity to teach managers across the country and even some overseas bases such as Camp Zama, Japan.

DOD's later re-evaluation of the Institute's deployment to other nations again opened new vistas for Bob to visit countries like Rwanda that he had barely heard of or countries such as the

Solomon Islands that he only knew from history books and World War II news reels.

In addition to his teaching and research, Bob spent considerable time developing computer facilities and helping faculty and staff understand and use them.

It has been a remarkable tour of duty for Bob's 34 years with the Institute, from a handsome young man to a crotchety gray beard, enjoying it every step of the way. From a constant mug of coffee to a cup of decaf, Bob salutes the people along the way and the faculty and staff who have meant so much to him.

Bon Voyage.

Curriculum Developments, Teaching News, and Faculty/Staff Service

Dr. Robert McNab conducted a class for Leadership Development and Education for Sustained Peace January 2005 (Naval Postgraduate School) and provided analysis of the Iraqi economy and alternatives for the use of discretionary funds to the leadership of the 3rd BCT / 3rd I.D. U.S. Army.

Dr. Natalie Webb taught a session in economic decision making for the National Reconnaissance Office's Applied Innovation Course at NPS in early March.

Publications

Henderson, D., R. McNab, and T. Rozas (2005). The Hidden Inequality in Socialism. The Independent Review 9 (3), 389-412.

Mauskopf, J., Kitahata, M., Kauf, T., Richter, A., Tolson, J. (In Press) HIV Antiretroviral Treatment: Early versus Later. *Journal of Acquired Immune Deficiency Syndrome (JAIDS).*

Legendre, C., Beard, S.M., Crochard, A., Lebranchu, Y., Pouteil-Noble, C., Richter, A., Durand Zaleski, I. (*In Press*) The Cost-Effectiveness of Prophylaxis Valaciclovir in the Management of Cytomegalovirus after Renal Transplantation. *European Journal of Health Economics*

PERT (con't from p.1)

time as a random variable. The probability distribution of the activity time random variable is almost universally called a "beta" distribution.

The formal beta distribution used in probability textbooks and in many software packages including Microsoft Excel and Crystal Ball is a continuous distribution that has several nice properties:

1. The beta has finite limits. Many real-world random variables, including activity completion times, have finite limits. For example, task completion times have a lower bound that is greater than zero because it is impossible to complete a task in less than zero time, and this should be reflected in the model. By contrast, the normal distribution has a range from $-\infty$ to $+\infty$.

2. The beta can be asymmetrical. This property is desirable for modeling activity completion times, which are often skewed to the right by unlikely but severe overruns.

3. Finally, the beta distribution is flexible because it can take on many different shapes, including flat, narrow, U and inverted-U shapes. Some examples of beta distribution shapes are given in Figure 1 below (plotted as the probability density function or pdf). [1]

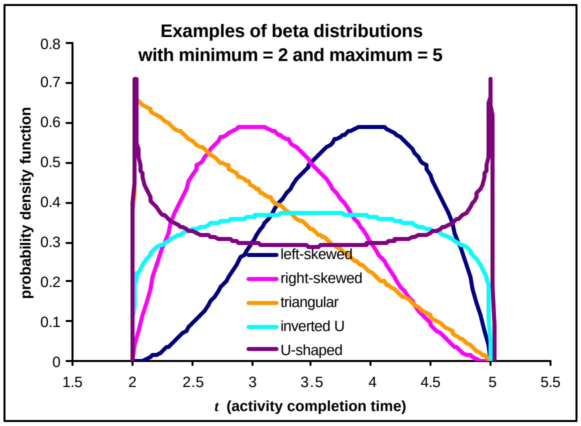


Figure 1

[1] For an introduction to pdf's, see Clemen (1996), p.239.

Simulation tools are increasingly available and accessible, which is enabling more users to bypass the PERT formulas. With simulation comes greater flexibility in choosing the shape of the distribution of task times. Therefore an understanding of the flexible beta distribution, and how to choose parameters that will give it the desired shape, becomes even more important.

Two parameters determine the location and range of the beta's pdf (these can be either upper and lower bounds or a location and range) and two parameters determine the shape (see Table 1). In Excel, the location and range are determined by parameters for the lower bound and the upper bound. The remainder of this article will use Excel's convention, with a lower bound (denoted *a*) and a upper bound (*b*), which will make it easier to compare beta with the PERT formulas.[2],[3] Unlike a and *b*, the parameters *a* and *b* have a natural interpretation, and should be easier to select for an analyst or expert to select when choosing a distribution for an activity time.

Table 1: Parameters of the beta distribution

a	These two parameters determine the shape of the distribution	
b		
a	Lower bound (optimistic value)	These two parameters are used directly in the PERT formulas.
b	Upper bound (pessimistic value)	

The shape of the beta distribution is determined by two numbers called the "shape parameters", which are often denoted a and b. The shape parameters do not have natural, operational, interpretations. Therefore, the following rules are designed to help an analyst or expert familiar with an activity in choosing parameter values so that the resulting beta distribution has the desired shape:

- **Mode:** The mode is the most likely value of the completion time, and is the value of completion time where the pdf reaches its peak.
  - Usually a and b are both greater than 1, which yields a beta distribution with a mode (most likely value) somewhere in the middle of the distribution, as in the first four distributions shown in Figure 1.
  - When a and b < 1, the beta looks U-shaped (see for example the purple distribution in Figure 1). In this case there are two modes, one at each end.
  - When both a = 1 and b = 1, the beta distribution is actually the same as a uniform distribution. There is no mode in this case.
- **Symmetry:**
  - When a = b, the distribution will be symmetric.
  - When a < b, the distribution will be skewed to the right (the mode will be closer to the left). This is common for activity completion times. The long tail on the right represents unlikely but difficult problems that cause severe delays.
  - When a < b, increasing the ratio $b:a$ will increase the skew.
  - When a > b, the distribution will be skewed to the left.
  - When a > b, increasing the ratio $a: b$ will increase the skew.
  - When a = 1 and b = 2 or vice versa, the beta distribution looks like a triangular distribution with the mode all the way on one side.

- **Standard deviation:** Given *a* and *b*, increasing the value of either a or b (or both) will narrow the distribution, and therefore decrease the standard deviation. (Note: this is true only for a and b > 1; these are the values that are usually used.) Figure 2 below shows betas with different standard deviations.

[2] In using Excel, it is important to note that the Excel function gives the cumulative distribution function (CDF); in contrast, we have plotted the pdf. For more information on how to use the CDF, see Clemen (1996), p.236-23.

[3] In Crystal Ball, however, the range of the distribution is specified by a parameter called its scale, and equal to $b - a$. In Crystal Ball, the distribution always has $a = 0$. The lower bound can be moved away from zero by adding a in a forecast cell.

The formulas for the expected value and standard deviation of a beta-distributed activity completion time are given below:

t_e^{beta} = expected completion time = $\frac{a}{a+b}\cdot(b-a)+a$ (1)

s^{beta} = standard deviation of completion time = $\sqrt{\frac{ab}{(a+b+1)\cdot(a+b)^2}}\cdot(b-a)$ (2)

In addition, the following formula gives the mode for a formal beta distribution:

mbeta = the mode (most likely) completion time $=\frac{a-1}{a+b-2}\cdot(b-a)+a$. (3)

The PERT formulas

As noted above, it is widely assumed that PERT uses a beta distribution for activity completion times. However, there is a distinction between the beta distribution described above and the beta distribution as used in PERT.

In its simplest form, the PERT method requires determining three estimates of the time required to complete each activity---the optimistic (*a*), most likely (*m*), and pessimistic (*b*) estimates (Moore and Weatherford, 2001, Chapter 14). Choosing a valid probability distribution or eliciting a probability distribution from an expert is difficult even when the expert has an intuitive assessment of the probabilities. Therefore, assessing a probability distribution on the basis of three parameters that have an operational interpretation–such as *a*, *b*, and *m*–is a very common practice.

In the PERT method, the three estimates are called the PERT parameters and are fed into the following two formulas to calculate the expected completion time and the variance of the completion time for that activity:

t_e^{PERT} = expected completion time = $\frac{a+4\times m+b}{6}$ (4)

s^{PERT} = standard deviation of completion time = $\frac{b-a}{6}$ (5)

In any good description of the PERT method, the expected completion time and standard deviation resulting from these formulas are referred to as estimates. The original paper that introduces PERT (then short for Program Evaluation Research Task) by participants in the planning of the Polaris project, says that the method is "the best that could be done in a real situation within tight time constraints" (Malcolm et al., 1959). Their time constraint was one month, but the tool they developed was so powerful that it is still in use today. In the mists of time, however, the humble admissions of the development team have been lost.

The PERT team made the assumption that the standard deviation s^{PERT}, was about $1/6$ of the range (*b*–*a*), yielding the formula in Equation (5). Given this assumption, Equation (4) represents a reasonable approximation of Equation (1) (Clark, 1962; Littlefield and Randolph, 1987). But just how accurate are these assumptions and approximation?

This question has been studied in some depth. The answer depends whether 1) the completion time is distributed according to a specific type of beta (the PERT-beta) or 2) the completion time has another beta distribution and the PERT formulas represent approximations.

If it is assumed that activity completion times have a specific type of beta distribution then it can be called the PERT-beta (sometimes called BetaPERT, as in Vose, 1996). The PERT-beta is a specific instance of the beta for which the formulas in Equations (4) and (5) are exact, i.e. $s^{PERT} = s^{beta}$ and $t_e^{beta} = t_e^{PERT}$. These formulas only hold for very restricted values of *a* and *b*. In particular, the PERT formulas are exact (Grubbs, 1962):

- when $a = 3-\sqrt{2}\approx 1.6$ and $b = 3+\sqrt{2}\approx 4.4$ (this produces a right-skewed beta), or
- when $a = 3+\sqrt{2}\approx 4.4$ and $b = 3-\sqrt{2}\approx 1.6$ (this produces a left-skewed beta), or

- When $a = b = 4$ (this produces a symmetrical distribution that resembles the normal).

Figure 2 shows the shape of the right-skewed PERT-beta. One of the desirable characteristic of the beta---its flexible shape---has been lost. Whereas the standard deviation can be very small or very large for a beta distribution, for the PERT-beta s^{PERT} is restricted according to Equation (5) and cannot depend on the specifics of a particular activity. For the asymmetric PERT-beta, the degree of asymmetry is also fixed.

A second interpretation of the PERT formulas is that they approximate the mean and standard deviation of a beta that might have another shape. This interpretation is commonly taken in the management science literature, where there have been many studies of the best way to approximate betas using three parameters. As discussed above, it is desirable to use three parameters because of the difficulty in eliciting more information and because the shape parameters have no natural interpretation. Triangular distributions, the PERT-beta, and other more complicated functional forms have been used (many are reviewed in Keefer and Bodily, 1983) to approximate to an underlying true beta.

It has been shown that the PERT mean and standard deviation formulas are a poor approximation for most beta distributions, as illustrated in Keefer and Verdini (1993) and in Keefer and Bodily (1983), who show average errors of 40% in the mean. The errors in the variance (s^2) average 549%. This is not surprising, as the PERT formulas depend only on the range (*b*–*a*), whereas Keefer and Bodily evaluated the performance of the PERT formulas at estimating the mean and variance of betas with many different shapes and widely varying variances.

Alternative formulas for expected completion time and variance have been proposed to adjust for various sources of error, and are summarized in Keefer and Bodily (1983). Many of these use estimates of the 5% and 95% confidence limits for activity completion time, rather than upper and lower bounds because these are easier for experts to estimate (for example, Keefer and Bodily, 1983 and Moder and Rodgers, 1968).

This means that if a particular activity does not fit the PERT assumptions–because it is more asymmetric, or has a larger or smaller variance–then it is better to either use alternative formulas, or to specify the beta distribution directly and use a network simulation to develop a probability distribution for overall project completion time.

Some users who want to build a quick simulation of a network without investing in project management software may use a general Monte Carlo simulation software, such as Crystal Ball, to produce a simulation of project completion times. However, many of the software packages that might be used for simulation do not have the PERT-beta built in. In these cases, a transformation is required to calculate the four beta parameters that will produce the PERT-beta distribution or other desired beta distribution. The mathematics of the relationship between the general beta and the PERT-beta are hammered out in, among others, Golenko-Ginzburg.

In DRMI's Flight Simulator case study, we use Monte Carlo simulation to generate a probability distribution for the completion time of the overall flight simulator project, implemented in Microsoft's Crystal Ball, an add-in for Excel. The case study uses the conventional PERT-beta parameters, but Crystal Ball does not include a PERT-beta option. Behind the scenes, we have had to make some calculations to calculate each activity's beta distribution parameters so that they correspond to the PERT-beta distribution.

One way to specify the distribution directly is by generating a starting estimate for the beta parameters *a*, *b*, a and b from the more easily obtainable PERT parameters, *a*, *b*, and *m*, then using the rules given above to adjust the a and b shape parameters until the desired shape is achieved. The upper and lower bounds (*a* and *b*) are identical in the PERT and beta formulas, and the following formulas give useful initial estimates for the shape parameters: $a = 2$; $b = \frac{b-a}{m-a}$.

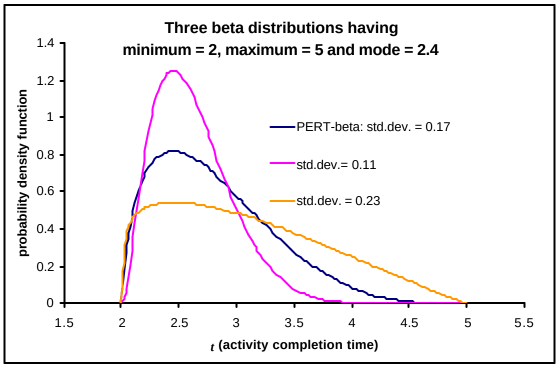


Figure 2

Take-home insights

The previous article in this series described how network effects can bias PERT and simulation to underestimate project completion times. This article delved into the modeling of individual activity completion times and how the PERT formulas can often underestimate the standard deviation of an individual activity's completion time.

Simulation can overcome the bias in the PERT standard deviation of completion times by bypassing the PERT formulas. This article has also provided guidance on how to choose parameters for a beta distribution so that a wider variety of shapes can be used to model activity completion times in a network simulation.

A final important issue to be aware of when using both the beta and the PERT-beta is that even though the PERT parameters have an easy-to-understand interpretation, estimates of *a* and *b* are not necessarily reliable. One reason these extreme values are difficult to estimate is that many experts are overly confident of their estimates (a common finding reviewed and reaffirmed by Brenner et al.).

In addition, errors in values elicited from experts are likely to be larger for extreme values (such as lower and upper bounds) because of availability bias. Availability biases essentially arise because people base their judgmental estimates on the information that comes readily to mind and in this sense "available" (Tversky and Kahnemann 1974). Information that is required to estimate extreme values for activity completion times will not tend to be available in this sense. The upper bound completion time is truly the worst-case scenario and depends on all possible eventualities that might delay the completion of an activity. It is not only onerous, but often impossible for an expert to identify all these eventualities. Like all fallible experts, even knowledgeable managers will tend to underestimate the pessimistic completion time, possibly by a wide margin.

Moder and Rodgers demonstrated this experimentally, even with people expert in PERT and the relevant technical area. For this reason they recommend using expert estimates of the 5- and 95-percentile values instead. It has also been shown that, for other psychological reasons, most people underestimate task completion times when they themselves will complete the task (Buehler et al., 1994).

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DRMI Course Catalog and Brochure

The 2005 course catalog and the Defense Resources Management Course brochure is now available. If you would like copies, please contact the Admin Office at 831-656-2104 (DSN 756) or send e-mail to DrmiAdmin@nps.navy.mil

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DRMC 05-3 23 May - 17 Jun 2005
DRMC 05-4 25 Jul - 18 Aug 2005
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