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Observations on Risk Analysis

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MASTER

OPERATED BY
UNION CARBIDE CORPORATION
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OBSERVATIONS ON RISK ANALYSIS
(with special reference to energy related problems)

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ABSTRACT

This paper briefly describes WASH 1400 and the Lewis report. It attempts to define basic concepts such as risk and risk analysis, common mode failure, and rare event. Several probabilistic models which go beyond the WASH 1400 methodology are introduced; the common characteristic of these models is that they recognize explicitly that risk analysis is time dependent whereas WASH 1400 takes a "per demand failure rate" approach which obscures the important fact that accidents are time related. Further, the presentation of a realistic risk analysis should recognize that there are various risks which compete with one another for the lives of the individuals at risk. A way of doing this is suggested.

"But in this world nothing can be said to be certain, except death and taxes." - Benjamin Franklin

1. INTRODUCTION

1.1 Applications.

Probability and statistics will not by itself prescribe appropriate energy policy; decisions will have to be made by specialists in these matters, but probability and statistics can be of substantial help to the energy specialist in making his decision. The following examples illustrate the kinds of applications which we anticipate.

When a new potentially dangerous technological change such as an airport, highway, or nuclear power plant is contemplated for a community, a rational approach will be to weigh the advantages and disadvantages before making a decision. One of the disadvantages is that accidents may cause fatalities and injury. How can we quantify this risk?

How can we compare the risks associated with alternative methods of energy production? For example, how does the risk of mine disaster and health damage associated with coal mining compare with the nuclear generator risk?

How do the risks of alternative methods of nuclear waste disposal compare with one another? What are the risks associated with transporting spent fuel to a suitable disposal area? Is it safe to leave uranium mine tailings unprocessed? What is the danger that underground storage will contaminate drinking water due to the mobility of subsurface water?

Now, switching to a more fundamental example, consider that organisms are exposed to "doses" alleged to have detrimental effect; the doses may, for example, be of radiation or a chemical substance. The organism may or may not "respond," for example, by developing a cancer.

Determination of the true relation between response and dose is an important but difficult task. It is important because it is a basic issue in assessing the risk of an activity for safety or health, and therefore, it is of fundamental concern for the government regulation of industrial activity, nuclear generators for instance. It is difficult because it is interdisciplinary, bordering on biology, medicine, genetics, physics, and chemistry; it has a strong statistical component. Data is hard to obtain and frequently it is only indirectly to the point.

Thus, as these examples suggest, with increased population density, environmental awareness and technological intensity the government in general and the Department of Energy in particular has become more involved in risk assessment and regulation. These are all difficult problems but they are not, as is sometimes thought, entirely new problems. "... the use of quantitative techniques in decision making associated with risk is still in its early stages and is highly formative," WASH 1400 (1975). This is only partly true; risk analysis has a probabilistic and statistical component going back at least to Daniel Bernoulli.

1.2 What is risk analysis (RA)?

Webster (1976) gives as the first meaning of risk: "the possibility of loss, injury, disadvantage, or destruction: CONTINGENCY, DANGER, PERIL, THREAT." "Risk is the potential for realization of unwanted,

negative consequences of an event," Rowe (1977). In the statistical literature the word risk is not used in the above sense. There are several statistical meanings of risk identified with actuarial risk theory, decision theory and competing risk theory. We return to these in Section 4.

Formally, risk of the kind being discussed in RA, may simply be a random variable. In the background there is an activity to be engaged in and a collection of events which could result. Which event does result is subject to chance. In this context, events are usually thought of as being unpleasant but they need not be. Associated with each event there is a consequence of the event occurring. If the consequence is numerical and if by risk we mean the uncertain consequence before the activity is engaged in, then in the language of probability, risk is a random variable. The events will have probabilities which can be transferred to the consequences to obtain the probability distribution of the risk. Of course, risks and random variables can be vector valued.

A special motivation for RA is the need for assessing the impact of technological innovation on societal safety through alteration of the environment. The purposes of RA are to choose between alternative actions or policies and to judge whether an activity exceeds minimum standards of acceptable risk. Thus RA may help in formulating new laws or regulations, assessing existing regulatory requirements, evaluating new designs, indicating needed repairs, formulating safety research and inspection priorities, developing of licensing guidelines and dealing with general safety issues. In the design task we may attempt to prescribe what process parameter values will produce the desired system safety characteristics with a prescribed probability.

RA i) identifies the potential outcomes, both good and bad, of actions or policies ii) quantifies as far as possible the consequences of the outcomes including who will bear the burdens and who the benefits iii) estimates the probabilities of the consequences and iv) weighs the good against the bad.

2. REACTOR SAFETY STUDY (WASH 1400)

WASH 1400 (1975), sometimes called the Rasmussen report, is the state of the risk analysis art, at least for energy related problems. The purpose of the report is indicated by its subtitle: "An Assessment of Accident Risks in U.S. Commercial Nuclear Power Plants." Till WASH 1400, it was not clear how one might approach such problems. The report consists of three parts, i) a popular, non-technical executive summary of 12 pages which gives the general impression that, all things considered, nuclear power is really quite safe, ii) a technical main report of 198 pages, and iii) a cubic foot of appendices indicating the vast amount of detail which went into the preparation of the report.

It is worthwhile for us to suggest the flavor of the WASH 1400 methodology; "The risk determination was divided into three major tasks.... Task I includes the identification of potential accidents and the quantification of both the probability and magnitude of the associated radioactive releases to the environment.... Task II uses the radioactive source term defined in Task I and calculates how the radioactivity is distributed in the environment and what effects it has on public health and property.... Task III combines the consequences calculated in Task II, weighted by their respective probabilities to produce the overall

risk from potential nuclear accidents. To give some perspective to these results, they are compared to a variety of non-nuclear risks." In Section 4. we suggest a way to make this comparison more complete and formal.

With regard to Task I, accident sequences are identified by means of logic diagrams called event trees. "The starting point for the development of an event tree is the event (failure) that initiates a potential accident situation." A typical initiating event is a pipe break which may cause a loss of coolant accident (LOCA). Initiating events must be identified by the analyst using technical information and engineering judgement. A necessary weakness of this and presumably other methods appears at this point: there is no way of being sure that an important initiating event has not been overlooked. An event tree consists of an initiating event and the success or failure response of each of the applicable engineered safety features.

"After identifying the accident sequences, we must assign the probability of occurrence of each engineered-safety-system failure in the particular sequence. Since no commercial reactor has ever experienced these failures, no empirical data on which to base estimates of system-failure rates exist. Thus it is necessary to use techniques that generate system failure rates from failures of components and subsystems. Fault-tree methodologies, developed by the Department of Defense and NASA to identify system design flaws, are extended to derive probability estimates for both the failure of individual nuclear safety systems and the accident sequences of interest. The failure rates of components and subsystems are determined from industrial experience with products similar to those either in nuclear service or in related use in other industries." Rasmussen (1974).

The following problem is typical and suggestive of the Fault-tree methodology computation: On demand, an engineering safety feature requires both A-C and D-C current to operate. The probabilities of loss of 1) all D-C power 2) off-site A-C power and 3) on-site A-C power are p_1 , p_2 , and p_3 respectively. What is the probability that the safety feature fails

to operate due to loss of power? Answer: $1 - (1 - p_1)(1 - p_2 p_3)$ if events are independent.

Figure 1, taken from Rasmussen (1974), indicates the nature of a typical filled out event tree. Note i) that the tree begins with the initiating event "pipe break"; ii) it is simplified in that only seven of the 2^4 possibilities need be considered; for example, if electric power fails then none of the engineering safety features will function; iii) P_2 is the answer to the just previously considered problem; iv) release category consequences with their probabilities are the output of the event tree; v) probabilities are approximated by omitting all $1 - P_i$ terms since P_i is small.

Common mode failures

From WASH 1400: "The most uncertain area in the study (is) related to whether potential common mode failures or dependent failures, could be properly identified."... "In a simplified way, common mode failures can be thought of as multiple failures caused by a single event or failure e.g. the same environmental condition."

One thought which might help in the treatment of dependent failures is that the list of initiating events might be enlarged and redefined to eliminate dependencies. Thus suppose that an analysis treats the two initiating events $P = \{\text{pipe break}\}$ and $T = \{\text{transient}\}$ and that we want to incorporate $F = \{\text{flood}\}$ and $H = \{\text{human error}\}$. Define the new initiating events F , $H \cap \bar{F}$, $P \cap \bar{F} \cap \bar{H}$, and $T \cap \bar{F} \cap \bar{H}$ and prepare four event trees for these initiating events. One branch of the first event tree would consider that a flood causes a pipe break and there is a human error in the attempted repair.

Figure 1. Typical Event Tree

The Lewis et al. report (1978) criticizes WASH 1400. They point to inadequacies in statistical methodology, particularly the uncritical use of the log-normal distribution. They question whether the quality and availability of the data base and the completeness of the study, vast as it is, is adequate to support the executive summary conclusion. They seem to be saying that the study is a good try but the uncertainty of its conclusions is understated and too substantial to support a decision on the safety of nuclear power. Shortly thereafter the Nuclear Regulatory Commission repudiated the conclusions of the executive summary, just in time for Three Mile Island.

3. DETERMINATION OF PROBABILITIES

Ideally we should estimate the probabilities of the events in a risk analysis by direct observation using the methods of Demography and Statistical Reliability, see Spiegelman (1976) and Mann et al. (1974). However, the events will often be catastrophic and, fortunately for the individuals at risk, quite rare. This is however unfortunate for the analyst as he will have little data to work with.

"The breaking up of a rare event into a series of more likely events is a basic principle of the event tree and fault tree techniques..."

WASH 1400 uses a per-demand failure rate approach synthesizing system failure rates by fault-tree and event-tree methodology into more readily available component rates. Thus in our Figure 1 and its discussion the P_i 's were (conditional) probabilities and we multiplied them together to obtain the probability of a consequence. But all is not as it seems. Lieberman (1976) complains, rightly,

about the use of probabilities greater than one. For example, on page 167 of WASH 1400 we find that P_{IE} , which was previously the probability of an initiating event, is now 10 transients per reactor year but we still multiply as in Figure 1 to obtain the probability of a consequence.

The answer here is correct under plausible assumptions. Let's simplify the WASH 1400 problem to the following: Suppose that transients occur at random in operating time at the rate of 10 per reactor year and that when a transient occurs the conditional probability that the safety system does not function and an accident results is 10^{-10} ($= q = 1 - p$). The probability of one or more accidents per reactor year is then

$$\sum_{i=1}^{\infty} (1 - p^i) 10^i \exp(-10)/i! = 1 - \exp(-10q) \\ \approx 10 \cdot q = 10^{-9}.$$

We still multiply things together; the error was one of exposition and failure to state assumptions.

The Lewis report suggests that in some cases it may be possible to do better, they refer to a review of boiling water reactor scram failures. The correct basis for that review amounts to the following:

Safety System Effectiveness Problem.

The rate of reaction in an atomic power plant is controlled at a safe level by the insertion of control rods. The times at which control is needed (called transients) are assumed to be a Poisson process with rate μ per year. Failure times of the control system is assumed Poisson with rate θ per year. Transients and control system failures are assumed independent.

Within time T , no transient will occur when the safety system is inoperable if, first, the safety system operates for time T , or second, the earliest safety system failure occurs at time t but no transient occurs before the end of the interval. Hence the probability of this event is:

$$P(T) = \exp(-\theta T) + \int_0^T \theta \exp(-\theta t) \cdot \exp[-\mu(T-t)] dt$$

$$= [\mu \exp(-\theta T) - \theta \exp(-\mu T)] / (\mu - \theta), \mu \neq \theta$$

Next assume that failure of the safety control system is not detected immediately but only at regularly scheduled tests of which there are N per year. The yearly probability that a transient will occur at a time when the safety system is inoperable is $1 - [P(N^{-1})]^N$. Thus we have a second entirely different basis for computing the annual probability of an accident.

The Lewis report seems to be suggesting that in some instances there may be a physical theory which can be used to obtain better probability estimates. Indeed this has to offer the best long term possibility for improvement; we simply need to know more about the physics of failure. This includes subjects like reliability, strength of materials, fracture mechanics, corrosion, wear, etc.

The above safety system example illustrates a second quite general point. Risk analysis is really time dependent. The time ordering of events is often important.

Do rare events play a special role? Are there things which we can do to analyse rare events which are not valid for arbitrary events? Yes, there are at least two ways of thinking which are particularly applicable to rare events. The first of these is extreme value theory advocated in the present application by Starr, Rudman and Whipple (1976).

As an example, consider the determination of the dose-response relation discussed in our introduction. Traditional methods of fitting the dose-response curve are probit and logit analysis, Finney (1964). Biologically motivated "hit theory" models lead to different distributions, see Turner (1975). Thompson and Funderlic (1979) obtain a Weibull relation as a consequence of the following threshold model:

- 1) An organism might or might not respond after exposure to dose X ,
- 2) the organism has a large number of critical targets, 3) each target has a dose threshold which if exceeded will cause a response in that target, 4) a single target response results in organism response, and 5) thresholds of targets are randomly chosen from some distributions.

Thus the organism responds if the dose exceeds the minimum target threshold and a minimal extreme value distribution is called for. Several sets of data are fitted and it turns out that the Weibull does as well as the traditional methods. The parameters of the Weibull have nice interpretations.

A second special role is suggested by the fact that the Poisson distribution is sometimes referred to as the law of rare events. The following is a version most useful for risk analysis.

Towards an Algebra of Rare Events.

To be concrete suppose that there are a large number, n , of different kinds of accidents which can occur independently of one another at an industrial plant and that we are interested in the summary process of accidents. Thus let $N_i(t)$ be the number of accidents of type i which occur up to time t . $N(t) = N_1(t) + \dots + N_n(t)$ is the total number of

accidents of all types which occur at the plant up to time t . Writing $M(t) = EN(t)$ and $M_i(t) = EN_i(t)$ then of course $M(t) = M_1(t) + \dots + M_n(t)$.

We define the above to be a system of rare events if for each t

$$i) \quad \lim_{n \rightarrow \infty} \max_{i=1, \dots, n} P[N_i(t) = 0] = 1,$$

and

$$ii) \quad \lim_{n \rightarrow \infty} \prod_{i=1}^n P[N_i(t) \leq 1] = 1,$$

We interpret i) as saying that an accident of any given type is unlikely; ii) says that two accidents of any one type are unlikely. The relation ii) is usually stated in the equivalent form

$$ii') \quad \lim_{n \rightarrow \infty} \sum_{i=1}^n P[N_i(t) \geq 2] = 0;$$

ii') has the consequence that $\lim_{n \rightarrow \infty} M_i(t) = P[N_i(t) = 1]$ and

$$\lim_{n \rightarrow \infty} M(t) = \lim_{n \rightarrow \infty} \sum_{i=1}^n P[N_i(t) = 1].$$

With this background of language, the Theorem of Grigelionis, see Gnedenko (1967, p. 428), states

Theorem. For a system of rare events, the necessary and sufficient condition that the summary process $N(t)$ converges to a Poisson process with $EN(t) = \Lambda(t)$ is that for any fixed s and t ($s < t$)

$$\lim_{n \rightarrow \infty} \sum_{i=1}^n P[N_i(t) - N_i(s) = 1] = \Lambda(t) - \Lambda(s).$$

Thus the summary process of accidents is approximately Poisson even though the various types may not be. One consequence is that the probability of no accident in time t is approximately

$$P\{N(t) = 0\} \approx \exp\left\{- \sum_{i=1}^n P[N_i(t) = 1]\right\}.$$

4. CONSEQUENCES, COMPARISON OF RISKS

The actuarial theory of risk, see Beard, Pentikäinen and Pesonen (1969), looks at things from the point of view of an insurance company. Here the consequences of the unwanted events are clear; they are the monetary claims which must be paid. The object of the theory is to determine premiums that will avoid depletion of the insurance pool and consequent ruin of the company by a run of bad luck.

In statistical decision theory, loss is monetary or utility loss and risk is expected loss. Business experts have their problems of risk and perhaps, with their profit motive they can assign values to the consequences of events and push through their cost-benefit analyses.

The idea of cost-benefit analysis is that cost will rise (roughly) linearly with activity level but, while initial benefit is easy to obtain, equal increments of benefit will require continually greater effort. Hence cost will rise to meet benefit and that is the level of activity which should be undertaken. Risk-benefit analysis then attempts to carry this accounting technique over into the social area to determine the amount of technological activity of a certain kind at which risk is balanced by benefit.

But it is not clear to what extent this Bernoulli-Von Neumann-Morgenstern-Wald theory can or should be carried over to things like reactor safety. It seems that reactor safety is in large part concerned with potential negative consequences to society. These negative consequences will be measured in terms of premature deaths, accidents, and compromised quality of living, as well as monetary loss. Devices like placing the cost of a fatality at 6000 man days of labor are hard to

defend. It is unlikely that we will be able to "price" many of the consequences which will be our primary interest.

Demographers have been studying problems of risk for many years. Perhaps the business concept has too often been employed where the demographic idea is more appropriate.

For the consequence of immediate fatalities perhaps risk should be measured relative to a mortality table such as that of Table 1, taken from the *World Almanac* (1978). The principle mathematical entity here is the force of mortality which interestingly is sometimes called the intensity of risk of dying.

Table 1. Average Lifetime in U.S., 1976

Source: Division of Vital Statistics, Public Health Service

<u>Age Interval</u>	<u>Number Living¹</u>	<u>Avg. Life Expect.²</u>	<u>Age Interval</u>	<u>Number Living¹</u>	<u>Avg. Life Expect.²</u>
0-1	100,000	72.8	45-50	93,043	31.4
1-5	98,488	72.9	50-55	90,747	27.2
5-10	98,207	69.1	55-60	87,310	23.1
10-15	98,033	64.2	60-65	82,282	19.4
15-20	97,865	59.3	65-70	75,084	16.0
20-25	97,391	54.6	70-75	66,114	12.8
25-30	96,747	49.9	75-80	54,060	10.1
30-35	96,147	45.2	80-85	39,540	7.9
35-40	95,452	40.5	85 and up	25,029	6.0
40-45	94,522	35.9			

(1) Of 100,000 born alive, number living at beginning of age interval

(2) Average number of years of life remaining at beginning of age interval.

It may be of some value to distinguish a subtopic of risk analysis which we might call safety analysis. Here the unwanted events are called accidents and the negative consequences are premature death, injury, pain, etc. The mortality of mankind imposes a constraint on any realistic

safety analysis. Perhaps it is the unpleasantness of this condition which causes this obvious fact to be omitted from many safety analyses. Here we see that the quotation from Franklin is precisely to the point. The question is not whether to gamble, it is how to gamble. The statistical discipline of competing risks may be a proper framework within which to analyse this subset of problems.

Competing risk theory hypothesizes a number of risks (diseases, accidents, etc.) which compete for the lives of individuals. For each individual one of these diseases will "win out" and the individual will die from that risk. The theory then attempts to predict the consequence of removing or adding a risk. For example, what would be the effect on life expectancy if a cure for smallpox were found? Similarly we might ask, What would be the effect on life expectancy if one hundred atomic power plants were added to the community?

Let Y , the random lifetime of an individual from the community, have distribution $G(y)$ and density $g(y)$. The force of mortality is defined as $h(y) = g(y)/\bar{G}(y)$ where $\bar{G}(y) = 1 - G(y)$; it has the following interpretation: If we know that an individual has reached age y then the probability that he will survive for an additional short time, Δ , is approximately $h(y)\Delta$.

If a new independent risk is introduced and the individual dies from either the new risk or one of the old, depending on which occurs earlier, then it is a theorem that the new risk force of mortality will add to that of the risks already present. Postulating that the new risk force of mortality is constant over age, say λ , then the probability that an individual will eventually die from the new risk rather than one

to which he was previously exposed is

$$\begin{aligned}\pi(\lambda) &= 1 - \int_0^{\infty} \exp(-\lambda y) g(y) dy \\ &= \lambda \mu - \lambda^2 \kappa/2 + o(\lambda^2)\end{aligned}$$

where μ and κ are the first and second moments of g and $o(\lambda^2)$ is a remainder term which if divided by λ^2 goes to zero.

Introduction of an additional risk will decrease the expected life length of an exposed individual. With the new risk included, expected life length will be

$$\begin{aligned}\int_0^{\infty} \exp(-\lambda y) \bar{G}(y) dy &= \lambda^{-1} \pi(\lambda) \\ &= \mu - \lambda \kappa/2 + o(\lambda).\end{aligned}$$

Thus the reduction in expected life length will be approximately $\lambda \kappa/2$.

For example, from Table 1, the 1976 United States experience is that $\mu = 72.8$ and $\kappa = 5625.41$. The latter value follows from Table 1 assuming average individuals to die at interval midpoints and using the fact that a person reaching eighty-five has average additional life expectancy of six years. From WASH 1400, if 100 nuclear power plants are introduced and nuclear accident were the only risk, the individual early fatality probability per year is 2×10^{-10} .

Thus the probability of fatality from nuclear accident rather than some already existing risk would be approximately $72.8 \times 2 \times 10^{-10}$ or 10^{-8} . The reduction in expected life length will be approximately $2 \times 10^{-10} \times 5625.41/2 = 6 \times 10^{-7}$ years or about 18 seconds. Of course, these mortality figures are no more accurate than their input and WASH 1400 is controversial; but here we are illustrating a method of presentation which would be applicable to any such study. For instance, if we change the

2×10^{-10} figure to 10^{-6} then $\pi(10^{-6}) = 7 \times 10^{-5}$ and the reduction in life expectancy due to introducing the new risk is about one day.

As in WASH 1400 let's place these figures in context by considering motor vehicle fatalities. Again we base our computations on the 1976 United States experience as given in the (1978) *World Almanac*. From Table 2-(2) it appears that the new driver ages of 15-24 are particularly prone to fatal motor vehicle accidents; hence an assumption of constant risk will not be valid and the previously explained methods will not be applicable. Table 2 outlines a method which is applicable for calculating what the age distribution of fatalities would be if the risk due to motor vehicle accidents could be eliminated. The 1976 proportion of deaths due to motor vehicle accidents was $45,800/1,912,000 = 0.024$. In Table 2 "all" risks refers to all nonnuclear risks and "other" refers to risks excluding nuclear as well as motor vehicle risks. The life expectancy would rise to 73.6 years if motor vehicle risks were eliminated. This follows from Table 2-(6) again assuming that average individuals die at midpoints.

Table 3 summarizes the competing risk presentation of the Reactor Safety Study in so far as early fatality risk is concerned. Looking at life expectancy seems to be an effective way of quantifying this kind of risk. The above computations are however deficient in that many fatalities due to nuclear accident will not be immediate. Further work is needed in order to quantify the risk of these delayed fatalities.

Table 2. Motor Vehicle Fatality Risk vs All Other

age interval	survival probabilities, all risks	fatality probabilities, motor vehicle	force of mortality			fatality probabilities other
			all risks	motor vehicle	other	
	(1)	(2)	(3)	(4)	(5)	(6)
under 5	1.000	.034	.0179	.0008	.0171	.0171
5-14	.982	.072	.0035	.0018	.0017	.0017
15-24	.979	.342	.0114	.0084	.0031	.0030
25-34	.967	.167	.0134	.0042	.0092	.0090
35-44	.955	.094	.0252	.0024	.0229	.0222
45-54	.930	.089	.0616	.0023	.0593	.0562
55-64	.873	.078	.1400	.0021	.1379	.1228
65-74	.751	.066	.2800	.0021	.2779	.2134
75-84	.541	.058	.5370	.0026	.5345	.2964
85 and over	.250	.000	1.0000	.0000	1.0000	.2582

81

(1) Proportion surviving to beginning of interval for all risks.

(2) Motor vehicle accident death proportions by age.

(3) Force of mortality for all risks; calculated from (1).

(4) = $0.024 \times (2)/(1)$.

(5) = (3) - (4).

(6) Fatality probabilities by age if motor vehicle accidental deaths were eliminated; calculated from (5).

Table 3. Probabilities of Eventual Death from Different Competing Risks

	All Risks but Nuclear	All Risks but Nuclear and Motor Vehicle	All Risks	
			$\lambda = 2 \times 10^{-10}$	$\lambda = 10^{-6}$
Other	0.976	1.0	0.976	0.976
Motor Vehicle	0.024	0.0	0.024	0.024
Nuclear	0.0	0.0	10^{-8}	7×10^{-5}
Life Expectancy (Years)	72.8	73.6	72.8(-18 sec)	72.8(-1 day)

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