Empirical Data for Pedestrian Flow Through Bottlenecks

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Summary. The number of models for pedestrian dynamics has grown in the past years, but the experimental data to discriminate between these models is still to a large extent uncertain and contradictory. To enhance the data base and to resolve some discrepancies discussed in the literature over one hundred years we studied the pedestrian flow through bottlenecks by an experiment performed under laboratory conditions. The time development of quantities like individual velocities, densities, individual time gaps in bottlenecks of different width and the jam density in front of the bottleneck is presented. The comparison of the results with experimental data of other authors supports a continuous increase of the capacity with the bottleneck width. The most interesting results of this data collection is that maximal flow values measured at bottlenecks can exceed the maxima of empirical fundamental diagrams significantly. Thus either our knowledge about empirical fundamental diagrams is incomplete or the common assumptions regarding the connection between the fundamental diagram and the flow through bottlenecks need a thorough revision.

1 Introduction

Studies of the dependence between the capacity and the width of a bottleneck for pedestrian flow can be traced back to the beginning of the last century [1, 2]. But up to now it is discussed controversially whether it increases stepwise or continuously with width. In the following the basic assumptions of these two positions are introduced.

Commonly the flow equation in combination with empirical measurements is used to calculate maximal flow values through bottlenecks [3–6]. With the width of the pedestrian facility, b, the flow equation can be written

$$J = J_s\, b \quad \text{with} \quad J_s = \rho\, v. \tag{1}$$

The specific flow, J_s, gives the flow per unit-width and is the product of the average density, ρ, and the average speed, v, of a pedestrian stream. The empirical relation between flow and density, $J = J(\rho)$, is called the fundamental diagram and with a given fundamental diagram the capacity of a facility is defined as the maximum of this function. In general it is assumed that for a given facility (e.g. corridors, stairs, doors) the fundamental diagrams for different b merge into one diagram for the specific flow J_s. Consequently the capacity, C, is assumed to be a linear function of the width, b.

Contrary to this, Hoogendoorn and Daamen [7, 8] claim that the capacity is growing in a step-wise manner. This statement is based on their observation that inside a bottleneck the formation of lanes occurs, resulting from the zipper effect during entering the bottleneck. The data in [7, 8] indicate that the distance between these lanes is independent of the bottleneck-width. This would imply that the capacity increases only when an additional lane can develop, i.e. that this would occur in a stepwise manner with increasing width [8]. Consequently, either the specific flow would decrease between the values where the steps occur or the flow equation in combination with the concept of a specific flow would not hold. One goal of this work is to examine this claim.

To resolve the discrepancies an experiment is arranged where the density and the velocity and thus the flow inside the bottleneck is measured while a jam occurs in front of the bottleneck. Our experiment is performed under laboratory conditions with a homogeneous group of test persons and equal initial conditions for the density and position of the test persons in front of the bottleneck. Exclusively the width of the bottleneck and the number of the pedestrians are varied. For a detailed discussion the results are compared with experimental data of other studies. In this article we concentrate on unidirectional pedestrian movement through bottlenecks under normal conditions. The term movement under normal means that panic or in particular non adaptive behavior which can occur in critical situation or under circumstances including rewards [9] are excluded. This contribution summarizes parts of an articles and two diploma thesis. The reader may consult [10–12] for more detailed discussions and additional results.

2 Experimental Setup

The experiment was arranged in the auditorium ‘Rotunde’ at the Jülich Supercomputing Centre (JSC) of the Research Centre Jülich. The configuration is shown in Figure 1. The group of test persons was composed of students and ZAM staff. The boundary of the corridor in front of the bottleneck and the bottleneck was arranged from desks. The height of the bottleneck assured a constant width from the hips to the shoulders of the test persons. The length of the bottleneck amounted to $l_{bck} = 2.8\ m$. The holding areas ensured an equal initial density of the pedestrian bulk in front of the bottleneck for each run. The distance from the center of the first holding area to the entrance of the bottleneck was three meter.

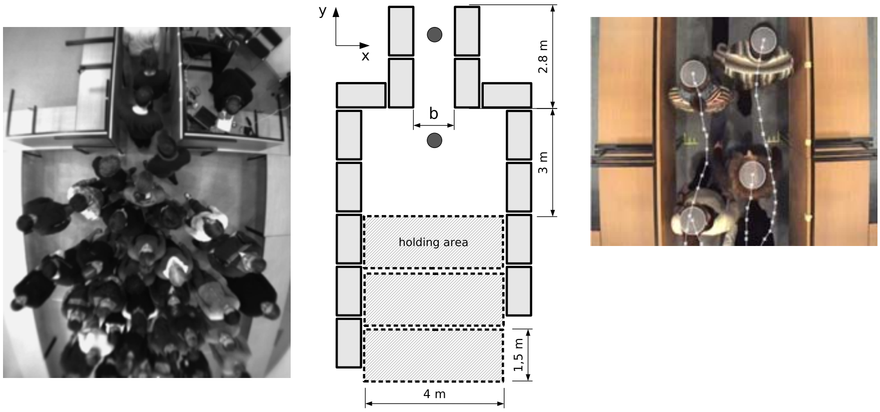

Fig. 1. Experimental setup. In the drawing the position of the video cameras are marked with circles. The holding areas are hatched. The left photo shows a picture of the camera in front of the entrance in the bottleneck. The right is a snapshot from the camera above the bottleneck. The trajectories are determined by marking the center of the head of each person manually.

A stepwise increase of the flow due to lane formation is expected more pronounced for small numbers of lanes. Thus the width of the bottleneck was increased from the minimal value of $b = 0.8\ m$ in steps of $0.1\ m$ to a maximal value of $b = 1.2\ m$. For every width runs are performed with $N = 20$, 40 and 60 pedestrians in front of the bottleneck. At the beginning of each run N test persons were placed in the holding areas with a density of $\rho_{ini} = 3.3\ m^{-2}$. They were advised to move through the bottleneck without haste but purposeful. It was emphasized not to push and to walk with normal velocity. The test persons started to move after an acoustic signal. The whole cycle of each run was filmed by two cameras, one situated above the center of the bottleneck and the other above the entrance of the bottleneck.

3 Data Analysis

3.1 Jam Density in Front of the Bottleneck

For the analysis of the jam density in front of the bottleneck only the runs with $N = 60$ are used. After selecting and extracting the pictures made by the camera located a half meter in front of the entrance, people are detected manually with the help of the software tool Censys 3D^{TM} [13]. To get an overview of the time dependence and the local values of the density this procedure was repeated for every second of the run. The measurement area of $1\ m^2$ was chosen directly in front of the bottleneck.

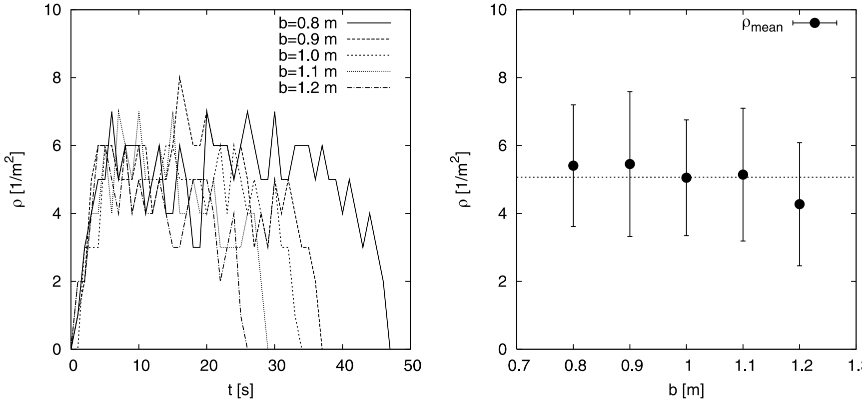

Fig. 2. Time dependence of density in an observation area of 1 m^2 located directly in front of the entrance (left). Different lines refer to different bottleneck widths. The resulting mean values of the stationary state as a function of the bottleneck width (right).

In Figure 2 one observes for every width b the following qualitative development of the density in time. In the first five seconds the pedestrian stream reaches the entrance to the bottleneck and the density increases rapidly. It follows a stationary phase with large fluctuations around a constant value. The length of the stationary phase decreases with increasing width. In the last ten seconds of every run the density decreases to zero. The large fluctuation in the second phase ranging from $\rho = 3$ to 8 m^{-2} can be explained by the small observation area of 1 m^2. However these fluctuations oscillate about a width independent mean value of $\rho = 5\ m^{-2}$. For the calculation of the mean value only the data of the second phase are used and as shown in the left figure they are consistent with the assumption that the width of a bottleneck has no influence on the density in front of the bottleneck. Indeed the fluctuations are very large and do not allow a conclusive judgement. Moreover it can not be excluded that this independence is restricted to small N and $b \geq 0.8\ m$.

3.2 Trajectories and Probability Distributions in the Bottleneck

The investigation of the flow insight the bottleneck is done by means of the trajectories (x_{ij}, y_{ij}, t_j). The index i marks the pedestrian, while j marks the sequence of the points in time. For the determination of the trajectories a manual procedure based on the standard video recordings of a camera above the bottleneck is used, see Fig. 1. For details of this procedure and how flow values, densities and velocities are extracted from the trajectories to study their time dependence we refer to [10].

In Figure 3 we have collected for the runs with $N = 60$ the trajectories, the probability distribution to find a pedestrian at the position x averaged over y and the probability distribution of the individual time gaps between

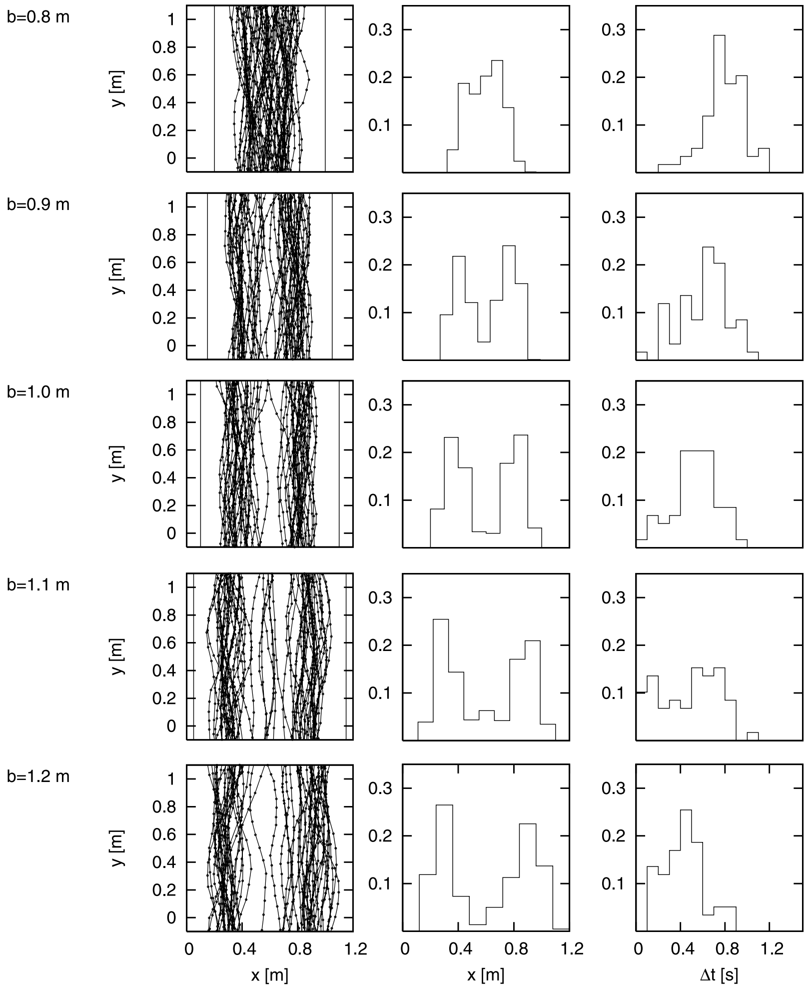

Fig. 3. For the runs with $N = 60$ and from top to bottom with increasing b: The trajectories (left), the probability to find a pedestrian at position x (middle) and probability distribution of the time gaps Δt_i at $y = 0.4\ m$ (right). For $b \geq 0.9\ m$ the formation of lanes is observable. However the distance between the lanes increases continuously with b leading to a continuous decrease of time gaps between two following pedestrians. Thus no indications of a stepwise change of the flow can be found.

the crossing of two adjacents pedestrians, Δt_i, at the center of the bottleneck at $y = 0.4\ m$. The double peak structure in the probability distribution for $b \geq 0.9\ m$ of the positions indicates the formation of lanes. The separation of the lanes is continuously growing with the width of the bottleneck. As a consequence of the zipper effect one expects also a double peak distribution for Δt. However this is not as articulated as in the separation of lanes in space. One can only observe a broadening of the time gap distribution with increasing b and a drift to smaller values. It is important to note that all changes as a function of the width are continuous except for the transition from one to two lanes and thus there are no indications of a stepwise increase or decrease in any observable.

3.3 Time Dependence of ρ, v_i, and Δt_i in the Bottleneck

For the first pedestrian in a run passing the bottleneck the velocity and density will be different from the velocity and the density of the following pedestrians. One expects that the density will increase while the velocity will decrease in time. A systematic drift to a stationary state, where only fluctuation around a constant value will occur, is expected.

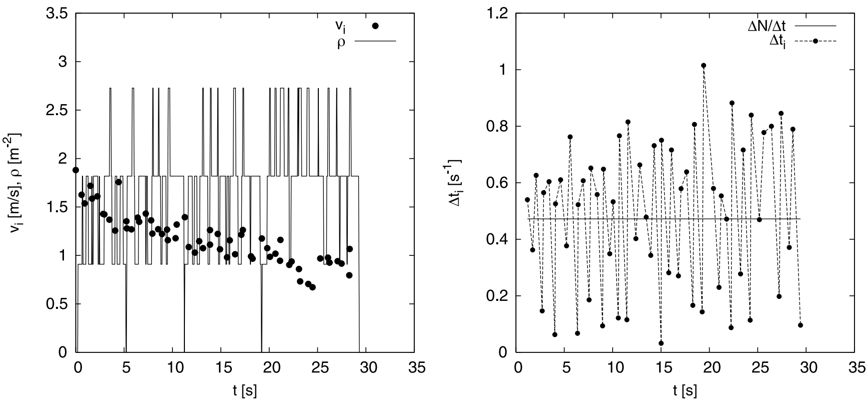

Fig. 4. Run with $N = 60$ and $b = 1.1\ m$. Development of individual velocity and density (left). While the velocity decreases the density increases. Development of the individual time gaps (right).

Figure 4 shows the time-development of the individual velocities and the density for the run with $N = 60$ and $b = 1.1\ m$. Plots for other runs can be found in [11]. The concept of a momentary density in this small observation area is problematic because of the small (1-4) number of persons involved and leads to large fluctuations in the density, see also Sect. 3.1. But one can clearly identify the decrease of the velocity and the increase of the density. For the individual time gaps a time dependence or a trend to a stationary state is hard to identify because the velocity decrease and the density increase compensate largely. A possible time dependence is hidden by large and regular jumps from small to high time gaps caused by the zipper effect.

To find stationary values for the velocity and density by means of regression analysis the tool *MINUIT* [14] for function minimization is used with the following model function borrowed from relaxation processes $f(t) = f_{stat} + A \exp -\frac{t}{\tau}$ for $f(t) = v_i(t)$ and $f(t) = \rho(t)$. The relaxation time τ characterizes the time in which a stationary state will be reached. The amplitude A gives the difference between the stationary state and the initial velocity or density. The velocity or density at the stationary state is labeled f_{stat}. For the fit we use the data of all three runs for one width with different N. Note, that the model function for the regression only describes the overall decrease in time and does not account for the density-fluctuations due to the small observation area or the fluctuations of the velocity in a stable state. Consequently we do not quote an error margin in Table 1.

Table 1. Results for the fit to $v_i(t)$ and $\rho(t)$

b $[m]$	v_{stat} $[m/s]$	A_v $[m/s]$	τ_v $[s]$	ρ_{stat} $[m^{-2}]$	A_ρ $[m^{-2}]$	τ_ρ $[s]$
0.8	1.18	0.354	3.55	1.42	−1.82	0.24
0.9	1.22	0.604	3.00	1.50	−1.20	0.95
1.0	1.17	0.485	3.83	1.59	−1.87	0.31
1.1	0.94	0.745	7.33	1.73	−1.30	2.10
1.2	0.99	0.836	5.63	1.70	−1.28	1.45

The results of the regression analysis are collected in Table 1. For $b \geq 1.0$ m even with $N = 60$ the stationary state is not reached, see e.g. Fig. 4. The results for A and τ indicate that the relaxation into the stationary state is almost independent of the width. However, for a final judgment more data or a larger number of test persons would be necessary. Nevertheless, the results are accurate enough to check at which position of the fundamental diagram the stationary state will be located. Again, the increase of the stationary values for the density ρ_{stat} can be explained by means of the zipper effect in combination with boundary effects.

4 Combined Analysis with Data from Other Experiments

4.1 Comparison with the Data of Other Experiments

In Figure 5 we have collected experimental data for flows through bottlenecks (left) and show how far our measurements fit into common fundamental diagrams (right). All measurements for bottleneck flows were performed under laboratory conditions. The amount of test persons ranged from $N = 30$ to 180 persons. The influence of panic or pushing can be excluded as the collection is

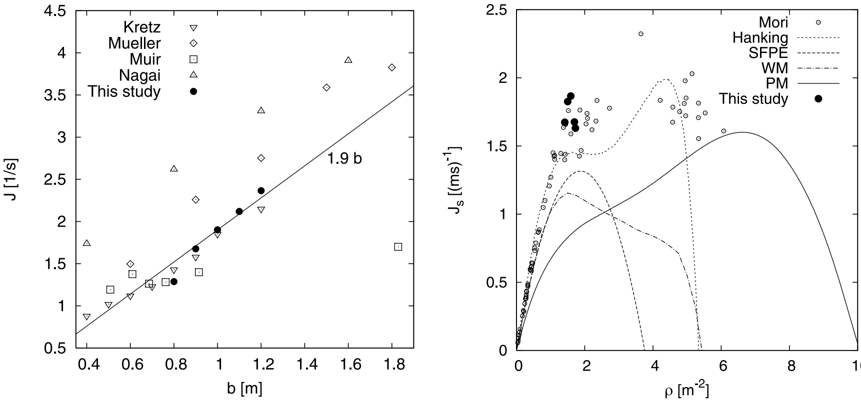

Fig. 5. Influence of the width of a bottleneck on the flow (left). Experimental data from other authors at different types of bottlenecks and initial conditions in comparison with the results of the above described experiment. Experimental data of the flow and the associated density in the bottleneck (right) in comparison with experimental data for the fundamental diagram of unidirectional pedestrian streams (Mori [15], Hanking [16]) and the specifications for the fundamental diagram according to the SFPE Handbook [6] (SFPE) and the guidelines of Weidmann [5] (WM) and Predtechenskii and Milinskii [3] (PM).

limited to measurements where the test persons were asked to move normally. However, the experimental arrangements under which this data were taken differ in many details which provide possible explanations for the discrepancies. Significant differences concern first the geometry of the bottleneck, i.e. its length and position with respect to the incoming flow, and second the initial conditions, i.e. initial density values and the initial distance between the test persons and the bottleneck. The flow measurements of [17] show a leveling off at $b > 0.6\ m$. But the range of the flat profile from $b = 0.6\ m$ to $b = 1.8\ m$ indicates that obviously the passage width is not the limiting factor for the flow in this setup. The data of [18] and [19] are shifted to higher flows in comparison with the data of [17, 20] and our data. The height of the flows in the experiments of Müller and Nagai can be explained by their use of much higher initial densities which amount to $\rho_{ini} \approx 5\ m^{-2}$. That the initial density has this impact is confirmed by the study of Nagai et al., see Fig. 6 in [18]. There it is shown that for $b = 1.2\ m$ the flow grows from $J = 1.04\ s^{-1}$ to $3.31\ s^{-1}$ when the initial density is increased from $\rho_{ini} = 0.4\ m^{-2}$ to $5\ m^{-2}$. The agreement between our data and the results obtained by Kretz indicates the minor importance of the bottleneck-length. This collection suggests that details of the bottleneck geometry and position play a minor role only, while the initial density in front of the bottleneck has a major impact.

4.2 Linear Dependence of Flow and Bottleneck-Width

As mentioned in the introduction one goal of this work is to examine if the flow or the capacity is a linear function of the width, b, of a bottleneck or if it grows in a stepwise manner, as suggested by [8]. Such a stepwise growth would question the validity of the specific flow concept used in most guidelines, see Sect. 1. However, the previous section has argued for the coherence of our data set and previous measurements. All of these results are compatible with a linear and continuous increase of the flow with the width of the bottleneck. Only around $b = 0.7\ m$ the data of [20] show a small edge. The edge is located exactly at the width where the zipper effect can begin to act, i.e. provides no evidence for a stepwise behavior in general. Moreover does the alleged stepwise increase of the flow follows from the assumption that inside a bottleneck the formation of lanes with constant distance occurs. In [8] this assumption is based on flow measurements at two different bottlenecks at $b = 1\ m$ and $b = 2\ m$. It is doubtful whether this results can be extrapolated to intermediate values of the width. In fact our data show no evidence for the appearance of lanes with constant distance (see Sect. 3.2, in particular Fig. 3).

4.3 Connection Between Bottleneck Flow and Fundamental Diagrams

The above results can be used to address a crucial question in pedestrian dynamics, namely the criteria for the occurrence of a jam and thus the connection between bottleneck flow and the fundamental diagram. Commonly it is assumed that jamming happens when the incoming flow exceeds the capacity of the bottleneck. Here the capacity of the bottleneck is defined as the maximum of the fundamental diagram for the specific flow, $J_s(\rho)$, times its width. Moreover most authors assume that in case of a jam the flow through the bottleneck persist on the capacity. However the comparison in Fig. 5 of the collected flow values (left) and fundamental diagrams (right) suggest a more complicated picture and cast doubt on assumptions outlined before. Our results from Section 3 can be used to examine which density and flow inside the bottleneck is present for a situation where a jam occurs in front of the bottleneck. In Sect. 3.1 it was shown that directly in front of the bottleneck the density fluctuates around $5\ m^{-2}$. Inside the bottleneck we found a density of $\rho \approx 1.8\ m^{-2}$ (see Tab. 1). Fig. 5 (right) indicates that the value for the stationary density is exactly located at the position where the fundamental diagram according to the SFPE-Handbook and the guideline of Weidmann show the maximum of the flow while the absolute value of the flow exceeds the predicted values. This seems to support the common jam-occurrence criteria. However, two observations cast doubt on this conclusion. Already when discussing the data of Müller and Nagai we have mentioned that higher initial densities result in higher flow values, i.e. that the maximal flow can not be near $\rho = 1.8\ m^{-2}$. In addition do the fundamental diagrams of Mori [15], Hanking [16] and PM [3] display a completely different shape. According to Mori and Hanking and in agreement with the specification of PM the flow will increase from $\rho \approx 1.8\ m^{-2}$ or stay constant with increasing density. Moreover does the level of the flow measured in our experiment conforms much better with their specifications. The most important conclusion which can be drawn from the data collection for fundamental diagrams and bottleneck flow is that the high flow values reached by increasing the initial density in front of the bottleneck can not be explained by the maxima of common fundamental diagrams. Moreover does the complicated picture of density values in front and inside the bottleneck suggest a revision of the common assumptions for bottleneck flow.

5 Summary

We have studied experimentally the flow of unidirectional pedestrian streams through bottlenecks under normal conditions. The jam-density in front of the bottleneck shows large fluctuations around a mean value of $\rho = 5\ m^{-2}$ independent of the width. The analysis of the trajectories inside the bottleneck shows that the density tunes around $\rho = 1.8\ m^{-2}$. For a small variation of the width quantities like the time gap distribution or the lane distance change continuously if the zipper effect is acting. The comparison of our data with flow measurements through bottlenecks of different types and lengths suggests that the exact geometry of the bottleneck is of only minor influence on the flow. Regarding the increase of the flow with the width all collected data are compatible with a continuous and linear increase, except for the edge at $b \approx 0.7\ m$ due to zipper effect is beginning to act. The linear dependency between the flow and the width holds for different kinds of bottlenecks and initial conditions. Hence it seems that the basic flow equation in combination with the use of the specific flow concept is justified for facilities with $b > 0.7\ m$. However, the rise of the flow through the bottleneck due to an increase of the initial density in front of the bottleneck from $\rho = 1.8\ m^{-2}$ to $5\ m^{-2}$ and the resulting high flow values through the bottleneck can not be explained by the maxima of common fundamental diagrams. Thus either the available measurements of density flow relation for pedestrian traffic are incomplete or the connection between bottleneck flow and fundamental diagram need a rigorous revision.

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