

Module

3

Process Control

Lesson

16

Special Control Structures: Predictive Control, Control of Systems with Inverse Response

Instructional Objectives

At the end of this lesson, the student should be able to

- Explain with an example the difficulty in controlling a process with dead time.
- Draw and explain the function of Smith Predictor Compensation Scheme.
- Explain the two schemes for predictive control in automatic gage control of a rolling mill.
- Given an example of a process with inverse response.
- Write down the transfer function of process with inverse response and sketch its step response.
- Suggest a suitable compensation scheme for control of a process with inverse response.

Predictive Control

It has already been mentioned earlier, how in a chemical process control transportation lag (time delay) comes into picture affecting the model and performance of the process. Model of a process having a time delay τ_d will have a term $e^{-s\tau_d}$ in its numerator of the transfer function. Processes having large time delays are normally difficult to control. A change in set point or disturbance does not reach the output until a time τ_d has elapsed. As a result, performance of the closed loop control system is normally sluggish and any change in set point or disturbance will give rise to large oscillations of the output before coming to a steady state value.

In order to improve the closed loop performances of such time delay systems, O.J.M. Smith in 1957 first suggested a modification of conventional PID control schemes for processes having large time delay. The scheme for taking a predictive action in presence of transportation delay in the system is better known as *Smith Predictor*.

Let us consider that the transfer function of the process is given by:

$$G_p(s) = e^{-s\tau_d} G(s) \quad (1)$$

where $G(s)$ represents the system model without the delay. The basic scheme for Smith Predictor is shown in Fig. 1. Here $G(s)$ is the conventional PID controller designed for the process $G(s)$. If the system model is exact, the output of the comparator-A would be zero and the outer loop can be ignored. The closed loop system can be simplified as the block diagram shown in Fig. 2. Since the time delay part is absent here, the controller will see the effect of control action much earlier and the sluggish response of the system will improve. The outer loop comes into play if the model of the process is not exact (normally that is expected). Fig. 1 can be redrawn as shown in Fig. 3 with the actual controller is shown inside the dashed line.

The performance of the Smith Predictor depends heavily on the actual knowledge of the plant model. Any change in the plant characteristics (particularly dead time) should be instantly taken care of, or otherwise, can cause deterioration of its performance. Besides, the hardware implementation of the controller using analog circuits is difficult. But the control scheme can be implemented with relative ease with a digital controller.

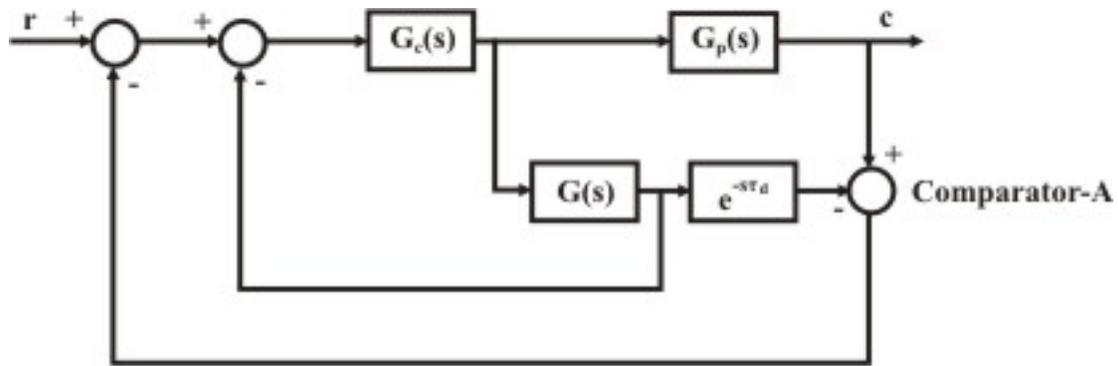


Fig. 1 Smith Predictor.

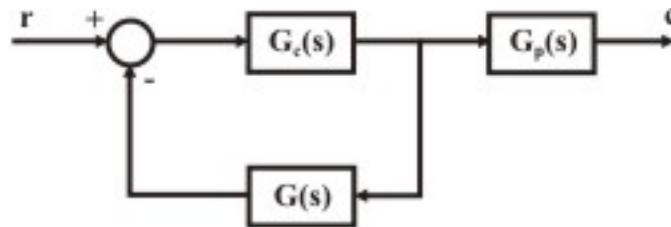


Fig. 2 Equivalent block diagram of Fig. 1 when the model is exact.

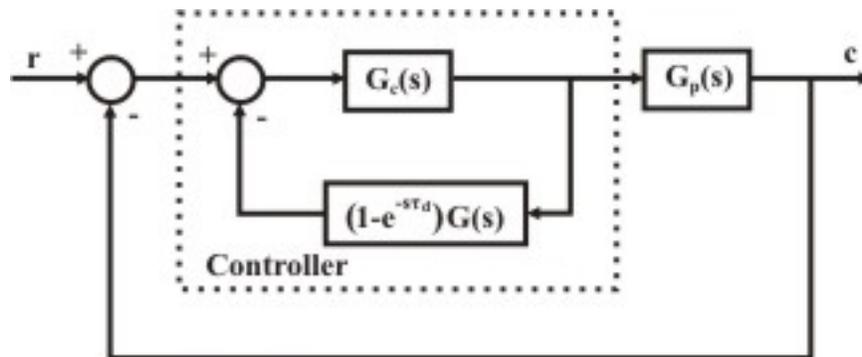


Fig. 3 Equivalent scheme of controller.

Application of Predictive Control in Gage Control of Steel Rolling Mills

In this section we shall give two examples of Predictive Control in control of gage thickness in steel rolling mills. *Automatic Gage Control (AGC)* is the most important control scheme in a rolling mill. Its main objective is to maintain the thickness of the sheet steel coming out of a rolling mill constant. The basic feedback scheme for AGC in a single stand rolling mill is shown in Fig. 4. The gage is controlled by varying the gap between the rollers in a stand. In fact, there are a number of stands in a rolling mill and the rolling is carried out in stages. Hydraulic actuators are normally used for roll gap adjustment. In this scheme, the gage of the strip is measured at the exit stand and compared with the reference gage command. The error is amplified to operate the servo valve of the hydraulic actuator. The basic control scheme shown here is P-type. Nucleonic detector is used for measurement of gage thickness at the exit stand.

But because of the fact that the thickness measuring device is installed at a distance from the roll, it will introduce transportation lag in the closed loop system. There will be considerable time lag to detect the variation of sheet thickness at the roll stand and that will lead to oscillatory and unsatisfactory behaviour of closed loop gage control.

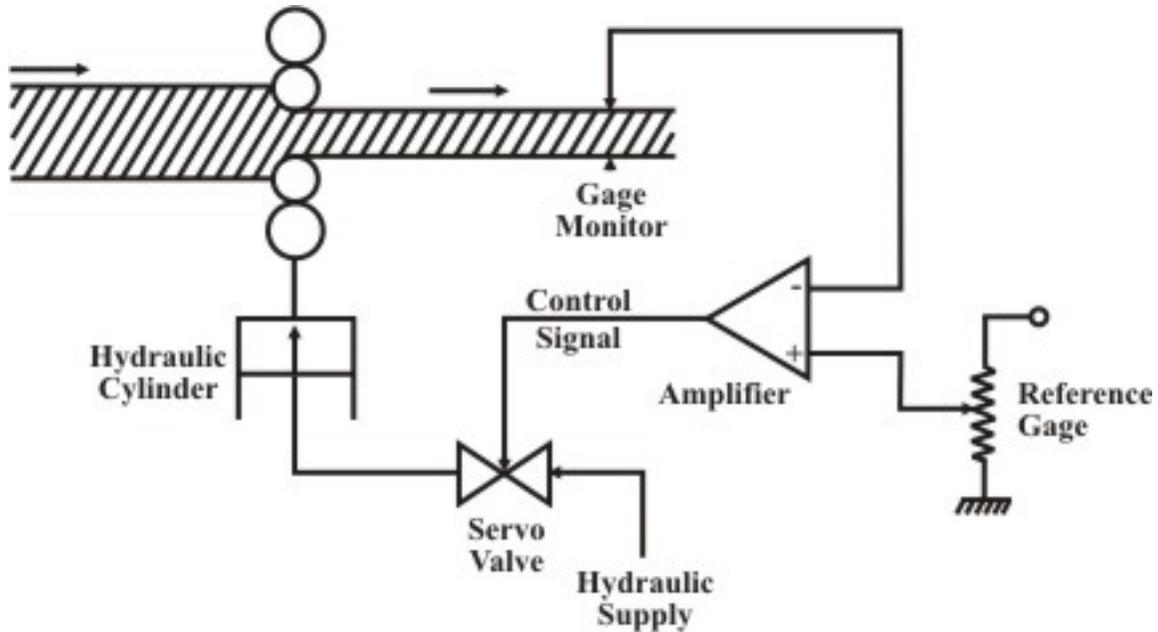


Fig. 4 Basic feedback loop for gage control.

In order to improve the performance of the closed loop scheme, Predictive Control mechanisms are added with the basic feedback scheme. Here the actual roll gap (and subsequently the gage thickness) is estimated at the roll stand. This can be achieved by two possible methods:

- estimating the roll gap
- estimating the gap thickness from constant mass flow principle.

In both the cases, the gap is estimated through an approximate model of the rolling stand.

Smith Predictor by estimating the roll gap

In this method, the gage thickness is predicted by estimating the roll gap using the expression:

$$h = C_0 + \frac{P}{K_s} \quad (2)$$

where h is the exit thickness of the rolled product, C_0 is the no-load roll gap, P is the roll force in the hydraulic actuator and K_s is the structural stiffness of the mill. The overall scheme can be represented as in Fig. 5.

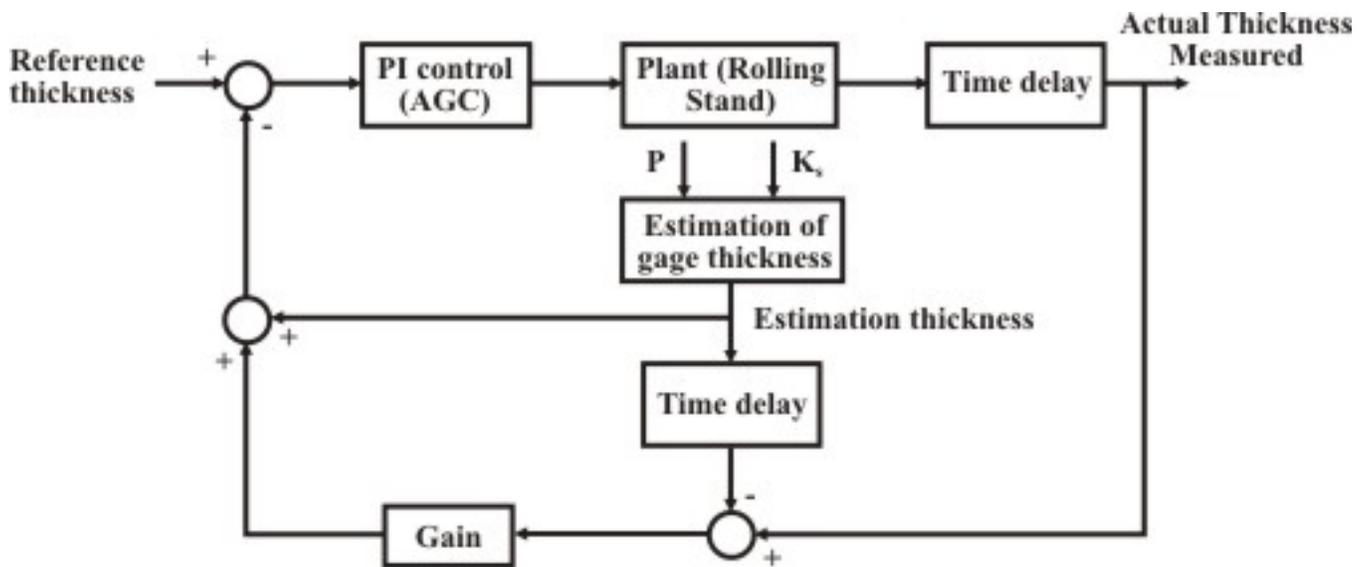


Fig. 5 Smith Predictor by estimating the roll gap.

Smith Predictor based on Constant Mass Flow principle

The thickness of the strip can also be predicted from constant mass flow principle. Consider a multi-stand mill. Let h_{i-1} and v_{i-1} be the thickness and the velocity of the strip at the inlet of the i -th stand (i.e. outlet at the $(i-1)$ th stand). So h_i and v_i are the corresponding parameters at the outlet of the i -th stand. Then from the principle of conservation of mass, we can write,

$$\text{Rate of mass flow in} = \text{Rate of mass flow out}$$

Considering the width of the strip to be same before and after the stand, we can write:

$$h_{i-1} v_{i-1} = h_i v_i$$

or,
$$h_i = \frac{h_{i-1} v_{i-1}}{v_i} \quad (3)$$

The velocities at the inlet and outlet of the stand can be measured by using a Laser Doppler velocity meter, or in a more conventional way by measuring the roll speeds at the two stands. However, some more correction factors are incorporated while predicting the exact gage thickness using constant mass flow principle. A scheme similar to Fig. 5 can be used here in the Smith Predictor scheme.

Systems with Inverse Response

We have seen different types of system response so far: first order system, second order system, system with time lag etc. Another type of system can also be classified with its typical step response pattern: system with inverse response. It is essentially a system whose transfer function is having a zero on the right half plane. This type of system is also called, *nonminimum phase system*.

Example of a system with inverse response

Before going into the details, let us consider a simple example of a system with inverse response. Consider the dynamic characteristics of a boiler drum in a water tube boiler of a steam power plant. High-pressure feedwater is pumped to the drum. Water from the drum circulates through the boiler tubes, gets heated and is converted to steam. This steam again comes back to the drum and subsequently is taken out through the steam flow line to the turbine. So the drum is filled up partially with water and partially with steam, both at high pressure. It is very important to control the water level of the drum at a desired level, by controlling the feedwater flow, with the varying demand of steam. The schematic arrangement can be shown as in Fig. 6.

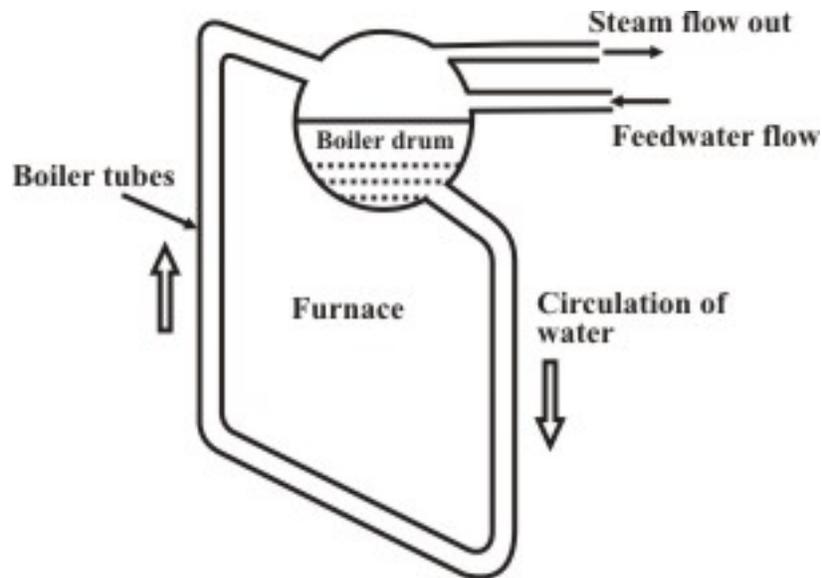


Fig. 6 A boiler drum.

The instantaneous level of water at the boiler drum is decided by the steam flow rate and the feedwater flow rate and it would reach a steady state when both are equal. Now suppose, the steam flow rate suddenly decreases, the feedwater flow rate remaining constant. At a first glance, it would appear that the drum level should rise. But actually the drum level will initially drop for some time before it rises and reaches a steady value. This is because of the fact that drop in steam flow rate will initially cause the rise in steam pressure in the drum. Due to the rise in pressure, the bubbles present inside the water in the drum will momentarily *shrink*. This will cause the temporary fall in the drum level. Similarly, for a sudden increase in steam flow rate, the drum level will momentarily *swell* before it drops down to a steady state value. A typical response curve of the drum level due to the sudden fall in steam level is plotted in Fig. 7.

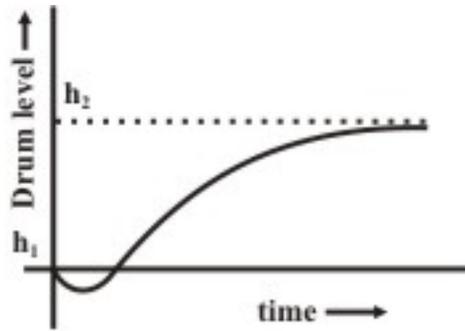


Fig. 7 Change in drum level due to sudden drop in steam flow rate.

Transfer function of a system with inverse response

The above response curve can be looked into as a combination of two first order process responses in opposition as shown in Fig. 8. The block diagram representation is shown in Fig. 9.

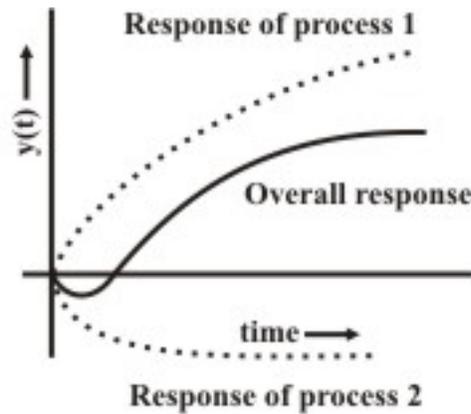


Fig. 8 Inverse response resulting from two first order opposing systems.

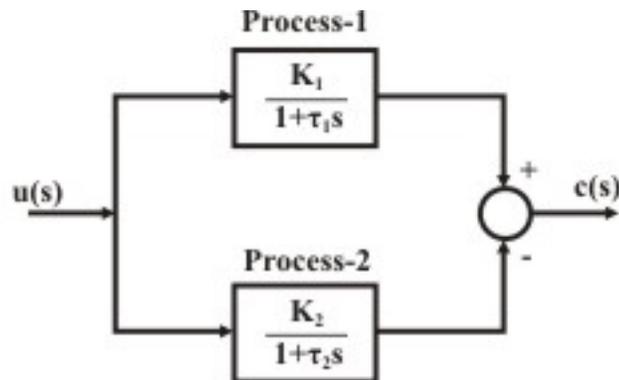


Fig. 9 Block diagram of two opposing first order systems.

The overall output response can be written as:

$$c(s) = \left[\frac{K_1}{1+\tau_1 s} - \frac{K_2}{1+\tau_2 s} \right] u(s)$$

or.
$$c(s) = \frac{(K_1 \tau_2 - K_2 \tau_1) s + (K_1 - K_2)}{(1+\tau_1 s)(1+\tau_2 s)} u(s) \quad (4)$$

Let us assume

$$\frac{\tau_1}{\tau_2} > \frac{K_1}{K_2} > 1 \quad (5)$$

Then for a step input, the response of process-2 will dominate during the initial phase, but ultimately, process-1 will dominate in the steady state. It can also be seen that under these two conditions, the system has a zero on the right half of s-plane (it is evident from the fact that $K_1 > K_2$ and $K_1 \tau_2 < K_2 \tau_1$). The inverse response is a typical characteristics of a *nonminimum phase system*, i.e. a system with an unstable zero.

Control of a System with Inverse Response

It is evident that control of a system with inverse response is difficult as in the case of control of a system with large time lag. For a closed loop time lag system with a simple feedback controller, the controller does not see any effect of control action till a time τ_d has elapsed. On the other hand, for an inverse system, the controller will see an opposite effect to the expected one. So naturally, some special arrangement, similar to a Smith Predictor scheme is needed for control of inverse systems. Such an arrangement is shown in Fig. 10. This also requires an *a priori* knowledge of the system model.

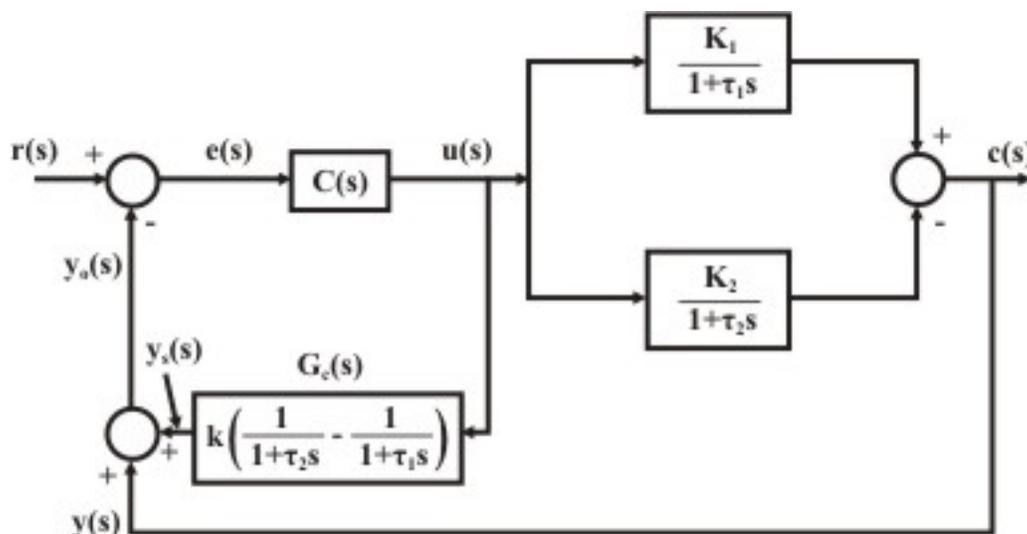


Fig. 10 A typical scheme for controlling a system with inverse response.

From Fig. 10, if we neglect the additional compensator loop with $G_c(s)$ then it is evident that the feedback information received,

$$y(s) = C(s) \frac{(K_1\tau_2 - K_2\tau_1)s + (K_1 - K_2)}{(1 + \tau_1s)(1 + \tau_2s)} e(s) \quad (6)$$

that has a zero in the right half plane. To eliminate the effect of inverse response, one additional measurement signal must be added that excludes the information of inverse response. That can be achieved by the loop through the compensator $G_c(s)$, that gives an additional output

$$\begin{aligned} y_s(s) &= C(s)G_c(s)e(s) \\ &= C(s)k \left(\frac{1}{1 + \tau_2s} - \frac{1}{1 + \tau_1s} \right) e(s) \end{aligned} \quad (7)$$

Combining (6) and (7), we can have,

$$\begin{aligned} y_0(s) &= y(s) + y_s(s) \\ &= C(s) \frac{(K_1\tau_2 - K_2\tau_1)s + k(\tau_1 - \tau_2)s + (K_1 - K_2)}{(1 + \tau_1s)(1 + \tau_2s)} e(s) \end{aligned} \quad (8)$$

Now the loop transfer function, i.e. transfer function between y_0 and e , will have a zero on the left half of s -plane, if the coefficient of s in the numerator of (8) is positive, i.e. using (6)

$$k > \frac{K_2\tau_1 - K_1\tau_2}{\tau_1 - \tau_2} \quad (9)$$

Thus it is evident that due the presence of the compensator, the inverse response behaviour (i.e. r.h.p zero) will not be felt by the controller. It can be also easily seen that the compensator in Fig. 10 has a similar configuration as in Fig. 6 for smith predictor. In other words, the compensator in Smith Predictor predicts the dead time behaviour of the process, while in the present case; the compensator $G_c(s)$ predicts the inverse behaviour of the process. The basic controller is normally chosen of P-I type.

Further improvement of compensator design for an inverse system has been reported in [4].

References

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2. K.J. Astrom and B.J. Wittenmark: Computer Controlled Systems, Prentice Hall of India, New Delhi, 1994.
3. V.B. Ginzburg: High Quality Steel Rolling: Theory and practice, Marcel Dekker Inc., NY, 1993.
4. W. Zhang, X. Xu and Y. Sun: Quantitative Performance Design for Inverse-Response Processes, *Ind. Eng. Chem. Res.* , vol. 39, pp. 2056-2061, 2000.

Review Questions

1. Draw the basic scheme of a Smith Predictor for controlling a process with a transportation lag and explain its principle of operation.
2. For proper operation of a Smith predictor, the model of the process must be known with sufficient accuracy- justify.
3. Explain a Smith predictor scheme used for automatic gage control in rolling mill.

4. What do you mean by a system with inverse system? Give an example.
5. A transfer function of a process with inverse response will have a zero on the right half s-plane – justify the statement.
6. Draw and explain the operation of a compensator for compensating the inverse response of a process in a feedback control scheme.

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