A comparison of Lenz lenses and LC resonators for NMR signal enhancement

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Abstract
High signal-to-noise ratio (SNR) of the NMR signal has always been a key target that drives massive research effort in many fields. Among several parameters, a high filling factor of the MR coil has proven to boost the SNR. In case of small-volume samples, a high filling factor and thus a high SNR can be achieved through miniaturizing the MR coil. However, under certain circumstances, this can be impractical. In this paper, we present an extensive theoretical and experimental investigation of the inductively coupled LC resonator and the magnetic Lenz lens as two candidate approaches that can enhance the SNR in such circumstances. The results demonstrate that the narrow-band LC resonator is superior in terms of SNR, while the non-tuned nature of the Lenz lens makes it preferable in broadband applications.

KEYWORDS
inductive coupling, LC resonator, Lenz lens, NMR

1 INTRODUCTION
Inductive coupling is often used in magnetic resonance imaging (MRI) and spectroscopy (MRS). Two inductances are inductively coupled if they are arranged in such a way that flux lines of one inductance penetrates the area enclosed by the other inductance and thus share a mutual inductance (M) as shown in Figure 1.

In magnetic resonance, the inductive coupling effect has been used for two applications: (i) Tuning and matching of MR detectors, which is achieved by placing an external inductance close to the MR detector. By changing the inductance’s relative position the mutual inductance is modified and which modifies the detector’s resonance frequency.1-6 (ii) The wireless transfer of energy (signal) from an MR detector, which is enabled by placing a pick-up coil which is wired to the spectrometer in close proximity to a non-wired MR detector. The signal recorded by the MR detector...
is transferred via inductive coupling to the spectrometer and is typically used to access samples within restricted areas,\textsuperscript{7} to locally enhance the signal-to-noise ratio (SNR),\textsuperscript{14-16} or to improve the handling comfort of MR probes.\textsuperscript{17-22}

The magnetic coupling between inductors is described by Faraday’s law of induction:

\[ \text{emf} = -\frac{d\Phi_B}{dt} \]  

where the electromotive force, \text{emf}, is the magnetic flux \( \Phi_B \) per time \( t \). The magnetic flux depends on the enclosed area \( A \) and the magnetic flux density \( B(d\Phi_B = (A \cdot B)) \). The signal transfer between the inductances depends on the magnitude of the magnetic flux density which is, in turn, proportional to the electric current \( (B(i)) \) in the primary circuit, and on the percentage of field lines linked to the secondary, which is proportional to the area (A) enclosed by the secondary inductance.

To ensure maximum signal transfer, the \text{emf} in the secondary coil is boosted by placing a capacitor in parallel with the inductance \( L_2 \). Thus, the circuit resonates at the Larmor frequency. This resonant inductive coupling configuration poses certain constraints on the MR detector design and its application.

The resonance frequency of the secondary circuit depends, besides its own parameters such as coil geometry and capacitor, on the load, that is, the sample, and the primary circuit through the mutual inductance. Thus, the LC resonator typically functions only with a dedicated primary coil and sample, and cannot be used efficiently when the loading conditions are altered. Due to possible occurrence of splitting,\textsuperscript{23} a large range for tuning and matching is of necessity. Thus, an implementation within an existing system (primary) is problematic, especially considering the reduced tuning and matching range, which reduces the adjustability for different loads and thus limits the range of examinable samples. Besides these disadvantages, a simple LC resonator only transmits a single frequency with high efficiency, and thus can only be used with limitations within a multiresonant primary coil.\textsuperscript{24,26}

An alternative approach to locally enhance SNR is to use the so-called Lenz lenses. A Lenz lens, as introduced by Schoenmaker et al.,\textsuperscript{27} consists of a single current carrying track, with an outer and an inner loop. Since in a Lenz lens, there is a single current carrying track, the outer loop of the Lenz lens carries the opposing current, while the current direction of the inner loop has the same direction as the source current. Since the magnetic flux density (B-field) in a current loop depends on the current and the radius of the loop, the magnetic flux density is higher in the inner loop, and thus, the magnetic flux is focused in a smaller area of interest.

In this paper, we will introduce a thorough comparison, supported by Matlab simulations, derived formulas, and experiments, of the various approaches utilized to enhance the sensitivity of the MR probe. First, we will describe the small wired probe (SWP) with inductance \( L_{a,S} \) and resistance \( r_a,S \). This coil has the same geometry as the sample, thus achieves highest filling factor and therefore it will be used as a reference. Then, we will introduce the big wired probe (BWP), with inductance \( L_{a,B} \) and resistance \( r_a,B \), that shows how the sensitivity decays as the filling factor gets lower. After that, we show how the LC resonator, with inductance \( L_c \), resistance \( r_c \), and capacitance \( C_c \), can enhance the sensitivity of the BWP. Finally, we introduce the lenz lens (LL), with outer loop inductance \( L_0 \) and inner loop inductance \( L_c \), as an alternative method to enhance the sensitivity of the BWP. These four coil configurations are summarized in Table 1.

2 | THEORY

2.1 | Simulation

In this section, we analyze the circuit models for the various coil configurations and explore the differences in performance via simulating these circuits in Matlab.

2.1.1 | Wired probe

First, we will consider the case when the MR probe is directly connected to the MR receiver. Figure 2 depicts a typical circuit model of the NMR probe. It shows the
detection coil shunted with a tuning capacitor $C_T$, which tunes the coil in a way such that it resonates slightly above the Larmor frequency and the real part of the parallel LC is 50 Ohms. This is formulated mathematically as

$$f_1 = \left(\frac{j\omega}{C_T}\right)k_r + \frac{j\omega}{L_c} = 50 + jX.$$  \hspace{1cm} (2)

The value of $C_T$ can then be readily obtained from the above equation by solving only the real part of the equation. The residual imaginary part of the equation is inductive in this case and can therefore be eliminated by the matching capacitor $C_M$ through solving the imaginary part of the following equation

$$\left\{\frac{1}{(j\omega + C_T)}\right\}k_r + \frac{j\omega}{L_c} + \frac{1}{(j\omega + C_M)} = 50.$$  \hspace{1cm} (3)

The voltage source $v_{\text{sig}}$, in Figure 2, represents the voltage of the NMR signal induced in the detection coil $L_a$. This can be calculated from the reciprocity principle\textsuperscript{28} for a 90° flip angle as follows

$$v_{\text{sig}} = K\omega_0 B_0 V_s M_0$$  \hspace{1cm} (4)

where $K$ is a factor that takes into account the inhomogeneity of $B_{\text{sr}}$, $\omega_0$ is the Larmor frequency, $B_0$ is the transverse magnetic field of the coil when a 1 A current flows through it, $V_s$ is the sample volume, and $M_0$ is the net magnetization which can be derived from the following expression

$$M_0 = \frac{N\gamma^2 h^2 I(I + 1)B_0}{3kT_s}$$  \hspace{1cm} (5)

in which $N$ is the number of spins within the sample, $\gamma$ is the magnetogyric ratio, $h$ is the reduced Planck constant, $I$ is the spin quantum number, $k$ is the Boltzmann constant, and $T_s$ is the sample temperature. The thermal noise associated with the NMR signal is modeled in Figure 2 by a voltage source $v_n$, whose amplitude is determined from the following formula

$$v_n = \sqrt{4kT_c\Delta fR}$$  \hspace{1cm} (6)

with $T_c$ being the coil temperature, $\Delta f$ the receiver bandwidth, and $R$ the AC resistance of the coil including the skin and proximity effects.

Obviously, according to the above equations, the SNR depends upon several parameters. However, for a fixed
sample volume and receiver bandwidth, it is the coil geometry that plays the major role in SNR. Needless to say, regardless of the coil type, the coil windings should be as close as possible to samples so that it encounters higher $B_u$, and as a result, a boosted SNR can be gained. This effect is demonstrated in Figure 3 by the blue curve with square markers. For this curve, the $x$-axis represents the ratio between the coil and sample diameters as the coil diameter increases while the wire width and thickness are kept constant. The $y$-axis shows the SNR relative to that when the coil and sample diameters are equal. The SNR, in this case, is obtained via simulating the circuit in Figure 2 excluding the noise of the RF receiver, and assuming a spherical sample of water with diameter $d_{\text{sample}} = D_{a,s}$ and single-loop surface coil with diameter $D_a$. The steep SNR degradation in this case is mainly due to the increased AC resistance of the coil thus increased noise on the one hand, and on the other hand due to the decrease in $B_u$ at the sample’s position.

### 2.1.2 NMR probe with LC resonator

As depicted by the blue curve with square markers in Figure 3, the SNR degrades largely when the diameter of the detection coil increases. This leads to the conclusion that we should always aim at a maximum filling factor. However, in certain cases, for example, for bench-top NMR spectrometers, the detector is non-changeable, and therefore, it is not feasible to replace such detector with one that exhibits a higher filling factor for small samples. A very good solution to such a problem is the use of a passive LC resonator. The inductor $L_c$, in this case, is designed to achieve maximum filling factor of the sample, while the

**Figure 3** Effect of increasing the coil-to-sample diameter ratio. (The blue curve with square markers): effect of increasing the diameter of the detection coil for a fixed sample volume on the SNR. (The green curve with circle markers): effect of increasing the detection coil’s diameter on the performance of the LC resonator used to enhance the NMR SNR. In this case, the inner coil, $L_c$, has a fixed diameter equal to that of the sample. (The red curve with rhombus markers): effect of increasing the detection coil’s diameter on the performance of the LL used to enhance the NMR SNR. In this case, the inner coil of the LL, $L_c$, has a fixed diameter equal to that of the sample, while the outer coil, $L_o$, has a diameter equal to that of the detection coil.

**Figure 4** Circuit model of an NMR probe with LC resonator for SNR enhancement.
capacitor $C_c$ is chosen in a way to make the $L_c$ resonate at the Larmor frequency $C_c = 1/(L_c \omega^2)$. Figure 4 shows the schematic diagram of the circuit model for an NMR probe with an LC resonator. Once the LC resonator is inserted inside the NMR probe, the tuning and matching will be disturbed due to the mutual inductance. The updated values of $C_T$ and $C_M$ can be recalculated via the following three equations

\begin{equation}
Z_x = \frac{V_x}{I_x} = r_{aB} + j\omega L_{aB} - \frac{(j\omega M_{LC})^2}{r_c + j\omega L_c + \frac{1}{j\omega C_c}}, \quad (7)
\end{equation}

\begin{equation}
\Re \left[ \frac{Z_x \cdot \frac{1}{j\omega C_M}}{Z_x + \frac{1}{j\omega C_M}} \right] = 50, \quad (8)
\end{equation}

\begin{equation}
\Im \left[ \frac{1}{j\omega C_M} + \frac{Z_x \cdot \frac{1}{j\omega C_M}}{Z_x + \frac{1}{j\omega C_M}} \right] = 0. \quad (9)
\end{equation}

After updating the values of the tuning and matching capacitors, the SNR can be calculated (excluding the noise of the RF receiver) directly by simulating the circuit and applying the superposition principle to find the overall noise due to individual contribution from each resistance. Worthy to remember, it is the noise powers which add, and not the voltages. Thus, the overall noise voltage is $V_n = \sqrt{V_{na}^2 + V_{nc}^2}$, where $V_{na}$ and $V_{nc}$ represent the noise contribution of $r_a$ and $r_c$ respectively at the probe terminals.

The green curve with circle markers in Figure 3 shows the SNR enhancement that can be attained through the use of an LC resonator. Moreover, it demonstrates how the efficiency of such resonator degrades when the diameter of the detection coil increases while the sample diameter (which is equal to the LC coil diameter) is fixed. This performance drop is due to the coupling between the coils which gets poorer with an increase in the detection coil’s diameter. Nevertheless, the LC resonator still provides significant enhancement even with large coil-to-sample diameter ratio. This is true as long as the LC resonator is tuned to the Larmor frequency, which is usually not a straightforward task if we consider the coil loading and the frequency splitting due to the mutual inductance. The effect of the resonance frequency deviation from the Larmor frequency is demonstrated in Figure 5.

2.1.3 | NMR probe with Lenz lens

The LC resonator, as demonstrated in the previous subsection, is essentially a narrow band solution that is highly sensitive to frequency deviation. Therefore, if one wants to operate the LC resonator in different magnets then one repeatedly has to go through a tedious process of tuning. Furthermore, for extremely large detection coils, compared to sample’s geometry, the efficacy of the LC resonator decreases remarkably, particularly if the resonator is not exactly at the Larmor frequency. These major drawbacks of the LC resonator make it useless in certain circumstances. Surprisingly, on the other hand, a non-tuned wide-band magnetic Lenz lens (LL) can provide adequate SNR enhancement in such circumstances where the LC resonator...
fails. The LL comprises two electrically connected coils: the inner coil, \( L_c \), which is usually designed in a way such that it achieves high filling factor of the sample, and the outer coil, \( L_b \), which is designed in a way to achieve maximum inductive coupling with the detection coil, \( L_{a,B} \). Due to high coupling, \( L_b \) collects the majority of the flux of \( L_{a,B} \) and converts it to a large current. This current flows in \( L_c \) resulting in a high \( B_a \) field focused in the sample. As a result of the reciprocity principle, the high \( B_a \) field yields a high NMR signal induced in \( L_c \), which is focused in the sample. As a consequence, the SNR of the BWP with LC resonator relative to that of the SWP can be calculated as

\[
\frac{\text{SNR}_{\text{BWP}}}{\text{SNR}_{\text{SWP}}} = \frac{\text{SNR}_{a,B}}{\text{SNR}_{a,S}} = \frac{D_{a,B} \sqrt{\frac{r_a}{r_a}}}{D_{a,B} \sqrt{\frac{r_a}{r_a}}}.
\] (13)

### 2.2.2 | NMR probe with LC resonator

Considering the circuit in Figure 4 of the probe with an LC resonator, if the resonator is tuned to the Larmor frequency, \( j \omega L_c = 1/(j \omega C_c) \), then the real part of Equation 7 reduces to

\[
\Re[Z_a] = r_{a,B}(1 + K_{ac}^2 Q_{a,B} Q_c)
\] (14)

where \( K_{ac} \) is the coupling factor between coils, \( Q_{a,B} \) is the quality factor of \( L_{a,B} \), and \( Q_c \) is the quality factor of \( L_c \). Thus, the SNR of the probe with LC resonator can be calculated for a planar single-loop detection coil \( L_c \) with diameter \( D_c \) as

\[
\text{SNR}_{\text{LC}} \propto \frac{B_c}{I_{a,B} \sqrt{r_{a,B}(1 + K_{ac}^2 Q_{a,B} Q_c)}}
\] (15)

\[
\propto \frac{B_c}{I_{a,B} \sqrt{r_{a,B}(1 + K_{ac}^2 Q_{a,B} Q_c)}}.
\]

The relation between \( I_a \) and \( I_{a,B} \) can be straightforwardly found from Figure 4 as follows

\[
\frac{|I_a|}{|I_{a,B}|} = \frac{\omega M_{ac}}{r_c}
\] (16)

which, upon insertion into Equation 15, results in

\[
\text{SNR}_{\text{LC}} \propto \frac{K_{ac} \sqrt{Q_{a,B} Q_c}}{D_c \sqrt{r_c} \sqrt{1 + K_{ac}^2 Q_{a,B} Q_c}}.
\] (17)

Remembering that the coils \( L_c \) and \( L_{a,S} \) have the same geometry, thus \( D_c = D_{a,S} \), and \( r_c = r_{a,S} \). Therefore, the SNR of the BWP with LC resonator relative to that of the SWP can be found as

\[
\frac{\text{SNR}_{\text{LC}}}{\text{SNR}_{\text{SWP}}} = \frac{\text{SNR}_{a,C}}{\text{SNR}_{a,S}} = \frac{K_{ac} \sqrt{Q_{a,B} Q_c}}{\sqrt{1 + K_{ac}^2 Q_{a,B} Q_c}}.
\] (18)
2.2.3 | NMR probe with Lenz lens

In Figure 6, the impedance $Z_e$ was given by Equation 10. Thus, the real part of $Z_e$ will be

$$\Re\{Z_e\} = r_{a,B} + \frac{\omega^2 M_{ab}^2 (r_b + r_c)}{(r_b + r_c)^2 + (\omega L_b + \omega L_c)^2}. \quad (19)$$

Thus, the sensitivity of the BWP with the LL, that has a single-loop inner coil whose diameter is $D_c$, is calculated as

$$\text{SNR}_{\text{LL}} \propto \frac{B_c}{I_{a,B} \sqrt{r_{a,B}}} \left( \frac{\omega M_{ab}}{(r_b + r_c)^2 + \omega^2 (L_b + L_c)^2} \right). \quad (20)$$

The relation between $I_c$ and $I_{a,B}$ can be directly found from the circuit model of the LL as follows

$$\left| \frac{I_c}{I_{a,B}} \right| = \frac{\omega M_{ab}}{\sqrt{(r_b + r_c)^2 + \omega^2 (L_b + L_c)^2}}, \quad (21)$$

After substituting Equation 21 and performing some mathematical manipulations, Equation 20 reduces to

$$\text{SNR}_{\text{LL}} \propto \frac{K_{ab} \sqrt{Q_{a,B} Q_b}}{D_c \sqrt{r_b + r_c}} \frac{1 + Q_{\text{LL}}^2}{1 + Q_{\text{LL}}^2} + K_{ab} Q_{a,B} Q_b \quad (22)$$

where $Q_{\text{LL}} = \omega (L_b + L_c)/(r_b + r_c)$. Remembering that $D_c$ is equal to $D_{a,B}$, the SNR of the BWP with LL relative to the SWP can be formulated as

$$\text{SNR}_{\text{LL}} \approx \frac{\text{SNR}_{\text{LL}}}{\text{SNR}_{\text{SWP}}} = \sqrt{\frac{r_c}{r_b + r_c}} \frac{K_{ab} \sqrt{Q_{a,B} Q_b}}{\sqrt{\left( \frac{1 + Q_{\text{LL}}^2}{1 + Q_{\text{LL}}^2} \right) + K_{ab} Q_{a,B} Q_b}}. \quad (23)$$

3 | EXPERIMENTAL VERIFICATION

3.1 | Measurement protocol

We recorded a series of measurements to compare three different Lenz lenses (LL), and an inductively coupled LC resonator with a SWP. For signal transmission, a BWP with 50 mm diameter was exploited as a Tx/Rx coil. The SWP, the coil of the LC resonator, and the inner coil of the LL have the same diameter of 5 mm. The outer diameter of the Lenz lenses is swept from 12.5 mm (small) to 22.5 mm (middle) to 45 mm (big). All test lenses and coils are manufactured on an FR4 substrate with a 35 μm thick copper layer by an external supplier (CONTAG AG, Germany) and are depicted in Figure 7. For all measurements, water was used as a sample. A PMMA sample container with a diameter of 4.5 mm diameter and a height of 2.5 mm resulting in a sample volume of 40 μL is used. The sample is placed in the isocenter of a horizontal bore Bruker BioSpin 94/20 small animal MR scanner at a static field strength of 9.4 T. Before spectra acquisition, an automated shim procedure was applied, which consists of a $B_0$ map acquisition, a map shim, and an iterative shim. The flip angle was calibrated manually with a nutation spectrum acquisition experiment. The excitation pulse length was swept at an excitation pulse power of 1 W. From the nutation spectra, the probe efficiencies were computed with the gyromagnetic ratio of protons of $\gamma_{1H} = 42576 \text{ MHz}/\text{T}$. All water spectra were recorded in one shot (without averaging) at a receiver bandwidth of 10 kHz. All linewidths were approximately constant at 20-30 Hz. The SNRs were determined from the peak height of the water signal and the noise over a 2 ppm region, and the integrals were computed from 8 ppm to 2 ppm for each spectrum via the TopSpin software (Bruker BioSpin GmbH, Germany). The acquired data is summarized in Table 2, which also includes the theoretical (simulation and calculation) results. In addition to that, the table shows the efficiency of each coil configuration computed from the measured flip angle, excitation power, and the length of the excitation pulse.

3.2 | Experimental results

With a high filling factor and minimum transmission losses, the SWP resonator is the most efficient at a measured SNR of 10959. The SNR of the SWP is used as a reference (100% rel. SNR), and subsequently, the SNR values of the other coils and lenses were normalized with respect to it. As expected from the theoretical predictions, the inductively coupled LC resonator exhibited the closest performance to the SWP resonator with a measured relative peak SNR of 78.2%, which perfectly matches the theoretically predicted relative SNR values of 77.3% (simulated) and 78% (calculated). The Tx/Rx BWP measured a relative peak SNR of 12.8% (predicted at 7.2% with simulation and 7.6% with calculation), while the big Lenz lens with an outer diameter of 45 mm showed a relative peak SNR of 25.9% which again matches the values estimated theoretically. Thus, the big Lenz lens approximately doubles the SNR of the Tx/Rx BWP.

On the other hand, the smallest LL with a relative SNR of 0.6% did not present a remarkable enhancement of the BWP’s SNR, which is quite unlike the theoretical
calculations. We presume this lower performance is owed to the small linewidth of the Tx/Rx BWP. It should be noted that the SNR of the spectra varies with the linewidth, which could not be exactly matched for all measurements, due to the close proximity of the copper conductors for some of the coils and lenses. The integrals are less affected by the linewidth, thus the integral of the small Lenz lens (15%) is marginally better than the Tx/Rx BWP’s integral (14%).

4 | CONCLUSION

We simulated and experimentally tested a number of MR coil configurations and reported an extensive comparison of their performance. Namely, these configurations comprised a SWP, a BWP, and a BWP with inductively coupled LC resonator and Lenz lens. As expected, the SWP performs superior to all other coils for the chosen sample, since it has an optimal filling factor as well as the most efficient signal transmission (best $B_\text{f}/I$). Therefore, whenever possible, this coil should be used.

On the other hand, when it is not possible to use a coil with optimum coil/sample geometry, then as the coil’s size increases with respect to the sample’s dimensions the filling factor decreases and, as a result, the sensitivity of the MR probe decreases dramatically. Two candidate solutions can, in such a case, be used to enhance the performance of the BWP. These are the LC resonator and the Lenz lens. The results demonstrated that the LC resonator can achieve a performance close to that of the SWP, which makes it, in general, preferable to the Lenz lens. However, the simulations and calculations showed that this is true only when the Q of the LC resonator is sufficiently high, and the resonance hits exactly the Larmor frequency. These requirements of high Q and exact resonance at the Larmor frequency are hard to satisfy simultaneously, since the higher the Q the larger the resonance split and thus the more tricky is the tuning and matching. Nevertheless, a reasonable compromise can usually be found.

In contrast, the Lenz lens shows inherently lower performance than the LC resonators. In best cases, it can improve the SNR of the BWP up to 30% of the optimum achievable SNR of the SWP. This renders it less attractive in general. Nevertheless, considering its broadband nature and its ability to focus, shape, and even reorient the $B_\text{f}$ field, the LL can be beneficial in multinuclear experiments and implantable devices in which cases direct wire connections and bulky tuning capacitors are not feasible.

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| TABLE 2 | Measurement results for different inductively coupled coils with a fixed inner coil diameter (ID) of 5 mm and various outer diameters (OD). The integrals are acquired over from 8 ppm to 2 ppm |
|-----------------|----------------|----------------|----------------|
| OD/ID in mm/mm  | (A) SWP | (B) LC resonator | (C) Big | (D) Middle | (E) Small | (F) BWP |
| Mes. Abs. SNR   | 10 959  | 8565            | 2743     | 1514       | 1401    |
| Sim. Abs. SNR   | 11 018  | 8517            | 2920     | 1817       | 793     |
| Mes. Rel. SNR in % | 100   | 78.2            | 25.9     | 13.8       | 12.8    |
| Sim. Rel. SNR in % | 100   | 77.3            | 26.5     | 16.5       | 7.2     |
| Cal. Rel. SNR in % | 100   | 78              | 26.8     | 14.9       | 7.5     |
| Linewidth in Hz  | 28.7   | 29.7            | 36.2     | 22         | 19.5    |
| Efficiency in $\mu T/\sqrt{W}$ | 167.8 | 148.8           | 58.7     | 24.7       | 16.2    |
| Normalized Integrals in % | 100   | 82              | 30       | 19         | 14      |

FIGURE 7  Top: Images of (A) the SWP, (B) the LC resonator, (C) the big, (D) the middle, (E) the small Lenz lenses with inner coil diameter of 5 mm, (F) the BWP, and (G) the sample holder. Bottom: Collected spectra from a 4.5 mm diameter 40 µL water sample with their normalized intensities in %. The normalized peak SNR values are given in round brackets, while the values for the normalized integrals (integrated from 8 ppm to 2 ppm) are given in square brackets.
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