On the Sharpness of Certain Local Estimates for $H^1$ Projections into Finite Element Spaces: Influence of a Reentrant Corner*

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Abstract. In a plane polygonal domain with a reentrant corner, consider a homogeneous Dirichlet problem for Poisson's equation $-\Delta u = f$ with $f$ smooth and the corresponding Galerkin finite element solutions in a family of piecewise polynomial spaces based on quasi-uniform (uniformly regular) triangulations with the diameter of each element comparable to $h$, $0 < h \leq 1$. Assuming that $u$ has a singularity of the type $|x - v_M|^\beta$ at the vertex $v_M$ of maximal angle $\pi/\beta$, we show: (i) For any subdomain $A$ and any $s$, the error measured in $H^{-s}(A)$ is not better than $O(h^{2s+1})$. (ii) On annular strips of points of distance of order $d$ from $v_M$, the pointwise error is not better than $O(h^{2d-\beta})$.

1. Context and Results. Let $\Omega$ be a polygonal bounded simply connected domain in the plane and consider the Dirichlet problem

\begin{align}
-\Delta u &= f & \text{in } \Omega, \\
u &= 0 & \text{on } \partial \Omega,
\end{align}

where $f \in C^\infty(\overline{\Omega})$. Let $\alpha_1 \leq \alpha_2 \leq \cdots \leq \alpha_{M-1} < \alpha_M$ denote the interior angles at the corners. Assume that there is only one vertex, $v_M$, of maximal angle and that the angle is reentrant, $\alpha_M > \pi$. For simplicity in notation set

\[ \alpha := \alpha_M, \quad \bar{\alpha} := \alpha_{M-1}, \quad \beta := \frac{\pi}{\alpha}, \quad \bar{\beta} := \frac{\pi}{\bar{\alpha}}. \]

Then $\beta < 1$ and $\beta < \bar{\beta}$.

As is well known, cf. Grisvard [4], Kellogg [5] or Kondrat'ev [6], the solution of (1.1) can be expressed in terms of polar coordinates $r, \theta$ centered at $v_M$ and with the positive $\theta$-axis along one leg as

\begin{align}
u &= a t_\beta + w; & t_\beta(r, \theta) &= \omega_0(r, \theta) r^\beta \sin(\beta \theta), \\
w &= o(r^\beta) & \text{as } r \to 0,
\end{align}

where $a$ is a constant and $\omega_0 \in C^\infty(\overline{\Omega})$ with $\omega_0 = 1$ for $r \leq r_0, \omega_0 = 0$ for $r \geq 2r_0$. We assume that $2r_0$ is less than the length of the shortest leg emanating from $v_M$ so that $t_\beta = 0$ on $\partial \Omega$.

Let $S_h, 0 < h \leq 1$, be finite element subspaces of $H^1(\Omega)$ such that, for $\nu \in H^\gamma \cap H^1$ with $\gamma > 1$,

\begin{align}
\min_{x \in S_h} \|\nu - x\|_{H^1(\Omega)} &\leq C h^{\gamma-1} \|\nu\|_{H^\gamma(\Omega)}, & \gamma' = \min(\gamma, R),
\end{align}
where $C$ does not depend on $h$ or $v$ and where $R \geq 2$; cf. Ciarlet [2]. Here and below we use standard notation for the $L_2$-based Sobolev spaces $H^\gamma$ and $\tilde{H}^\gamma$; cf. Adams [1]. $H^{\gamma}(A)$ for $\gamma > 0$ shall refer to the dual space of $\tilde{H}^\gamma(A)$ with respect to the pivot space $L_2$, i.e., for $w \in L_2(A)$,

$$\|w\|_{H^{-\gamma}(A)} := \sup_{v \in C_0^\infty(A) \setminus \{0\}} \frac{\int_A vw}{\|v\|_{H^\gamma(A)}}.$$

The $\tilde{H}^1$ projection of $u$ into $S_h$, $P_h u$, is defined by

$$(1.4) \quad (u - P_h u, \chi)_{H^1(\Omega)} := \int_\Omega \nabla (u - P_h u) \cdot \nabla \chi = 0 \quad \text{for all } \chi \in S_h,$$

i.e., $P_h u$ is the Galerkin finite element solution of (1.1). (The effect of numerical integration is not considered in this note.)

On interior subdomains $A$ of $\Omega$ away from the corners the solution $u$ is smooth and hence, for commonly used finite element spaces, approximable to "high" order, typically $O(h^R)$ in $L_2(A)$. Numerical observations show that, for finite element spaces without special arrangements to treat corner singularities, the error in $u - P_h u$ on $A$ is generally not of this "high" order. This is often referred to as a "pollution" effect from the corners.

For $A \subseteq \Omega$ and with the error measured in a negative norm $H^{-\gamma}(A)$, a standard duality argument using (1.3) gives immediately an upper bound $O(h^{2\gamma})$ for the error, for any $\epsilon > 0$. ($\epsilon = 0$ can be taken in most cases.) If $a \neq 0$ in (1.2), it has long been felt that the error is not better than $O(h^{2\gamma})$ for general finite element spaces; this is sometimes also referred to as "pollution", even when $A = \Omega$.

As for previous proofs that "pollution" (in the second sense) occurs, we cite the following two works.

(i) An example by Babuška and Bramble with $\Omega$ the $L$-shaped domain, $\beta = 2/3$, and regular uniform meshes. Given $\epsilon > 0$, for each $h$ there exists $u_h$ such that

$$\|u_h - P_h u_h\|_{L_2(\Omega)} \geq c h^{4/3} \|u_h\|_{H^{4/3}(\Omega)},$$

where $c > 0$ is independent of $h$. This example was given in [10, Section 7, Example 4] but a full proof has never appeared.

(ii) A result of Dobrowolski [3, Theorem 7.1]. He considered a family of "unrefined" meshes in the sense that if $a \neq 0$ in (1.2), then there exists $c > 0$ such that

$$(1.5) \quad \min_{\chi \in S_h} \|u - \chi\|_{H^1(\Omega)} \geq c h^\beta,$$

and he showed that then

$$\|u - P_h u\|_{L_2(\Omega)} \geq c h^{2\beta}.$$

For piecewise polynomial spaces on a family of triangulations of $\Omega$, (1.5) would hold if each mesh contained merely one element $\tau_h$ at $v_M$ with its largest inscribed disc of radius $\geq c h$, $c$ positive and independent of $h$. To see this, note that by a simple scaling argument we have already

$$\min_{\chi \text{ polynomial of degree } \leq R - 1} \|r^\beta \sin(\beta \theta) - \chi\|_{H^1(\tau_h)} \geq c h^\beta.$$
Thus, (1.5) would follow for \( u = a t_\beta \). Since, by [4], [5], [6], \( w := u - a t_\beta \in H^{1+\sigma_\epsilon}(\Omega) \), \( \sigma = \min(2\beta, \bar{\beta}) > \beta \), we have from (1.3) that \( \|w - P_h w\|_{H^1} \leq C h^{\sigma - \epsilon} = h^\beta o(1) \) for \( \epsilon \) small enough, where \( \sigma' = \min(\sigma, R - 1) > \beta \). Thus (1.5) would follow for a general \( u \) with \( a \neq 0 \).

In this context we mention the interesting structure results of Nitsche [8]. They seem less successful in explaining the present “pollution” from corners than in investigating the corresponding “pollution” from boundary singularities in one-dimensional singular Sturm-Liouville problems [9]; cf. also Schreiber [13, Section 6.2].

Our first result in this note generalizes the results of Babuška, Bramble and Dobrowolski mentioned above.

**Theorem 1.1.** Assume (1.3), (1.5) and that \( a \neq 0 \) in (1.2). Let \( A \subseteq \Omega \) be any subdomain of \( \Omega \) and \( s \) any nonnegative number. There exist positive constants \( c \) and \( h_0 \) such that, for \( h < h_0 \),

\[
\|u - P_h u\|_{H^{-s}(A)} \geq c h^{2\beta}.
\]

The proof will be furnished in Section 2.

We shall next describe the second result of this note. We shall have to be more precise about various properties of the finite element spaces. For simplicity, cf. Remark 1.1, consider edge-to-edge triangulations parametrized by \( h, 0 < h \leq 1, \) of \( \Omega \) into disjoint triangular elements \( \tau_i^h, i = 1, \ldots, I_h \), and let \( S_h \) consist of functions \( \chi \) such that \( \chi \in H^0(\Omega), \chi = 0 \) on \( \partial \Omega \) and \( \chi|_{\tau_i^h} \) is a polynomial of total degree \( R - 1 \geq 1 \). Let the family of meshes be quasi-uniform (a.k.a. uniformly regular), i.e., let there exist positive constants \( c \) and \( C \) independent of \( i \) and \( h \) such that, with \( \rho_i^h \) denoting the radius of the largest inscribed disc of \( \tau_i^h \),

\[
ch \leq \rho_i^h \leq \text{diam}(\tau_i^h) \leq Ch \quad \text{for all } i, h.
\]

For brevity, let us call such a family \( S_h \) a “quasi-uniform Lagrange” family.

In Schatz and Wahlbin [11] it was shown that, for \( x \) close to \( v_M \), for any \( \epsilon > 0 \),

\[
|\langle u - P_h u \rangle(x)| \leq C \epsilon h^{2\beta - \epsilon} |x - v_M|^{-\beta}.
\]

This estimate was derived as a mix of two effects: local approximability of the solution and the “pollution” influence. In fact, “pollution” dominates in this estimate as can be seen via the following argument.

One knows from [4], [5], [6] that \( |D^\alpha u(r,\theta)| \leq C r^{\beta - |\alpha|} \) as \( r \to 0 \). Thus, with

\[
A_d = \{ x : d \leq |x - v_M| \leq 2d \} \cap \Omega,
\]

we have, for \( d \geq h^{1 - \delta}, \delta > 0 \), but \( d \) not too large (the remaining corners should be well away),

\[
\min_{\chi \in S_h} \|u - \chi\|_{L^\infty(A_d)} \leq C h^{Rd - R} = C h^{2\beta d^{-\beta} \left( \frac{h}{d} \right)^{R - 2\beta}} = h^{2\beta d^{-\beta} o(1)}.
\]

The result analogous to (1.6) for the five-point difference scheme and various classical ways of imposing the boundary conditions was given in Laasonen [7].

Our second result establishes the sharpness of (1.6).
Theorem 1.2. Let $S_h$ be a quasi-uniform Lagrange family. Assume that $a = 0$ in (1.2).

Then, for any $\delta > 0$, there exist positive constants, $c, d_0$ and $h_0$ such that with $A_j$ as in (1.7) and $h^{1-\delta} \leq d \leq d_0$, $h \leq h_0$,

$$||u - P_h u||_{L^\infty(A_j)} \geq c h^{2\beta} d^{-\beta}. $$

Again, the proof will be given in Section 2.

Remark 1.1. Theorem 1.2 can be established for more general finite element spaces than quasi-uniform Lagrange families. In fact, it holds under the general assumptions of [11, Section 2] if furthermore (1.5) is assumed. The proof is the same, but we do not wish to repeat the rather lengthy hypotheses of [11] in this note.

2. Proofs. Before giving the proofs of Theorems 1.1 and 1.2 we shall collect some more precise information about the problem (1.1) and the decomposition (1.2). The exact results can be found in [4], [5], [6]. For motivation one notes that away from vertices the solution $u$ of (1.1) is smooth, whereas at a vertex $v_i$ of angle $\alpha_i$ one has, in polar coordinates centered at that vertex and with $\beta_i = \pi/\alpha_i, \gamma_i \in \mathbb{Z}^+ \cup \{0\}$,

$$u(r, \theta) = a_i r^\beta \sin(\beta_i \theta) + b_i r^{2\beta_i} \sin(2\beta_i \theta) (\ln r)^{\gamma_i} + \text{smoother terms.}$$

The exact results are as follows.

For any $\epsilon > 0$ there exists a constant $C_\epsilon$ such that

$$||u||_{H^{s+1}(\Omega)} \leq C_\epsilon ||f||_{H^{s+1}(\Omega)}. $$

Let $\Omega_M$ be a neighborhood of $v_M$ avoiding all other vertices. Then for any $\epsilon > 0$, with $w$ as in (1.2), we have in fact that

$$(2.1) \quad |D^a w(r, \theta)| \leq C_{a, r} r^{2\beta - |a| - 1} \quad \text{as } r \to 0,$$

$$(2.2.1) \quad w \in H^{1+2\beta - \epsilon}(\Omega_M),$$

$$(2.2.2) \quad u \in H^{1+\beta - \epsilon}(\Omega \setminus \Omega_M),$$

$$(2.2.3) \quad \omega \in H^{1+\sigma - \epsilon}(\Omega), \quad \sigma = \min(2\beta, \beta) > \beta.$$

Proof of Theorem 1.1. The heart of the matter is the short calculation (2.4), once a suitable $u_0$ has been found. The rest of the proof is routine.

We first show that it suffices to treat a particular $u_0 = a_0 t^\beta + \cdots$ with $a_0 \neq 0$. For this let

$$\bar{w} := a a_0^{-1} u_0 - u.$$

Then, by (1.2) and (2.2.4), $\bar{w} \in H^{1+\sigma - \epsilon/2}(\Omega)$, with $\sigma > \beta$. Using (2.1) and (1.3), we have by the standard duality argument, writing $\bar{E} := \bar{w} - P_h \bar{w}$,

$$||\bar{E}||_{H^{-1}(\Omega)} \leq Ch^{\beta - \epsilon/2} ||\bar{E}||_{H^{1}(\Omega)} \leq C h^{\beta + \sigma - \epsilon},$$

where $\sigma' = \min(\sigma, R - 1) > \beta$. Thus, for $\epsilon$ small enough,

$$||\bar{E}||_{H^{-1}(\Omega)} = h^{2\beta} (1) \quad \text{as } h \to 0.$$

Our specific $u_0$ is constructed as follows. Let $x_0 \in \text{Int} A$, and let $A_0 \subset A$ be an annulus centered at $x_0$. If $A_0 = B_1 \setminus B_0$, where $B_0 \subset B_1 \subset A$ are concentric
discs, let \( \omega \in C^\infty(\overline{\Omega}) \) with

\[
\omega = \begin{cases} 
1 & \text{outside } B_1, \\
0 & \text{inside } B_0.
\end{cases}
\]

Let further \( G_0(x) \) be the Green's function for (1.1) with singularity at \( x_0 \), and set

\( u_0 := \omega G_0 \).

Then \( u_0 \in C^\infty(\text{Int}\Omega) \), \( u_0 = 0 \) on \( \partial\Omega \), and

\[
(2.3) \quad \text{supp}(\Delta u_0) \subseteq A_0 \subset \subset A.
\]

Also, \( a_0 \neq 0 \), as can be seen by classical means from the fact that \( G_0 \) is harmonic and positive in a neighborhood of \( \nu_M \). For completeness, we give the argument. Use a conformal map \( z^\beta \) to locally straighten the boundary. The transformed function \( \tilde{u}_0 \) is then harmonic and vanishes on a piece of the real axis; hence it is smooth and harmonic in a neighborhood of the origin by Schwarz' reflection principle and Weyl's lemma (or, by Schauder estimates). Thus, in new polar coordinates \( \rho, \phi \),

\[
\tilde{u}_0 = \sum_{j=1}^\infty A_j \rho^j \sin(j\phi)
\]

for \( \rho \) small enough; again, since \( \tilde{u}_0 \) is harmonic and vanishes on a piece of the real axis. Since \( \tilde{u}_0 \) is positive for \( \rho \) small, \( A_1 \) is positive by the orthogonality of \( \sin(j\phi) \) on \([0,\pi]\). Conclude by transforming back to original coordinates; \( A_1 \) corresponds to \( a_0 \).

We now have by (1.5), (1.4), Green's formula (that its use is permitted is easily checked) and by (2.3), setting \( E_0 := u_0 - P_h u_0 \),

\[
(2.4) \quad \chi^{2\beta} \leq \|E_0\|_{H^{-1}(A)}^2 = \left( E_0, u_0 - P_h u_0 \right)_{H^{-1}(A)} = \left( E_0, u_0 \right)_{H^{-1}(A)} - \int E_0(\Delta u_0)
\]

\[\leq \|E_0\|_{H^{-1}(A)} \|\Delta u_0\|_{H^1(A)}.
\]

Thus,

\[
\|E_0\|_{H^{-1}(A)} \geq \frac{c}{\|\Delta u_0\|_{H^1(A)}} \chi^{2\beta},
\]

which proves Theorem 1.1.

**Proof of Theorem 1.2.** The heart of the matter is (2.6) below, corresponding to (2.4) in the proof of Theorem 1.1. The rest of the proof consists of nontrivial technicalities.

Note that (1.3), (1.5) and all results of [11] hold for a quasi-uniform Lagrange family.

We shall first consider specific \( u_d \), depending on \( d \). Let \( \omega_d \in C^\infty(\overline{\Omega}) \) with

\[
\omega_d(x) = \begin{cases} 
1 & \text{for } |x - \nu_M| \leq d, \\
0 & \text{for } |x - \nu_M| \geq 2d.
\end{cases}
\]

Thus, \( \text{supp}(\nabla \omega_d) \subseteq A_d \), and we may assume by a scaling argument that

\[
(2.5) \quad \|\omega_d\|_{C^k} \leq C_k d^{-k}, \quad C_k \text{ independent of } d.
\]

Set now

\[
u_d := \omega_d r^\beta \sin(\beta \theta).
\]
Assume that $2d$ is less than the length of the shortest leg emanating from $v_M$ so that $u_d = 0$ on $\Omega_d$. Since $r^\beta \sin(\beta \theta)$ is harmonic, we find that $\text{supp}(\Delta u_d) \subseteq A_d$.

Let $E_d := u_d - P_h u_d$. We note that, with $c > 0$ independent of $d$ and $h$,

$$\|E_d\|_{H^1(\Omega)} \geq ch^\beta.$$  

This follows since, assuming that $\text{supp} \omega_d \subseteq \{w: \omega_0 \equiv 1\}$ with $\omega_0$ as in (1.2), we have $u_d = t_\beta + y_d$, where $y_d := (\omega_d - 1)t_\beta$. Here, by (1.5),

$$\|t_\beta - P_h t_\beta\|_{H^1} \geq ch^\beta.$$  

By (1.3) and a simple calculation of $\|y_d\|_{H^1}$ (using (2.5)), we find that, for $d \geq h^{1-\delta}$,

$$\|y_d - P_h y_d\|_{H^1} \leq C h^\beta y_d \leq C h^\beta y_d = Ch^\beta \left(\frac{h}{d}\right)^{1-\beta} = h^\beta_0(1).$$

As in (2.4), we now have

$$c h^\beta \leq -\int E_d \Delta u_d \leq \|E_d\|_{L^\infty(A_d)} \|\Delta u\|_{L^1(A_d)}.$$  

Using (2.5), it is easily calculated that

$$\|\Delta u_d\|_{L^1(A_d)} \leq Cd^\beta.$$  

Hence,

$$\|E_d\|_{L^\infty(A_d)} \geq c h^\beta d^{-\beta}.$$  

It remains to verify the same result for any $u$ with $a \neq 0$. This is now slightly more complicated than in the proof of Theorem 1.1 since the exact dependence on $d$ needs to be accounted for and our model functions $u_d$ depend on $d$. With

$$\bar{w}_d := au_d - u, \quad \bar{E}_d := \bar{w}_d - P_h \bar{w}_d,$$

we have to show that

$$\|\bar{E}_d\|_{L^\infty(A_d)} = h^2 d^{-\beta} o(1) \quad \text{as } h \to 0, \text{ for } h^{1-\delta} \leq d \leq d_0.$$

Let $\omega_0$ be the cutoff function in (1.2). We may assume that $\text{supp} \omega_d \subseteq \{x: \omega_0 \equiv 1\}$. Thus,

$$\bar{w}_d = a \omega_d t_\beta - u, \quad u = a t_\beta + w,$$

and so, with $w$ as in (1.2) and (2.2),

$$\bar{w}_d = \omega_d \bar{w}_d + (1 - \omega_0) \bar{w}_d = \omega_d \left(a \omega_d t_\beta - u\right) - (1 - \omega_0) u$$

$$= \omega_d \left(-w - a(1 - \omega_d) t_\beta\right) - (1 - \omega_0) u$$

$$= -\omega_0 w - a \omega_0 (1 - \omega_d) t_\beta - (1 - \omega_0) u = \bar{w}_d^1 + \bar{w}_d^2 + \bar{w}_d^3.$$  

We next quote a result from [11, Theorem 3.2] on local maximum norm estimates. For any $\epsilon > 0$, there exists $C_\epsilon$ such that

$$\|\bar{E}_d\|_{L^\infty(A_d)} \leq C \epsilon^{-1} \left\{ \min_{\chi \in S_\epsilon} \left( \|\bar{w}_d - \chi\|_{L^\infty(A_d)} + h\|\bar{w}_d - \chi\|_{L^\infty(A_d)} \right) + d^{-1}\|\bar{E}_d\|_{L^2(A_d)} \right\}.$$
where \( A'_d = \{ x : d/2 \leq |x - v_M| \leq 4d \} \cap \Omega \). (In the quasi-uniform context, cf. [12, Theorem 7.1] for a simpler proof.)

By well-known approximation results, cf. [2], using (2.8), (2.2.i) and a simple direct calculation on \( \widetilde{w}_d^2 \), we have, with \( A''_d = (A'_d + h) \cap \Omega \),

\[
(2.10) \quad \min_{x \in S_a} \left( \|\widetilde{w}_d - x\|_{L^2(A''_d)} + h\|\widetilde{w}_d - x\|_{L^2(A'_d)} \right) \\
\leq Ch^2\|\widetilde{w}_d\|_{L^2(A'_d)} = Ch^2\|\widetilde{w}_d^1\| + \widetilde{w}_d^2\|_{L^2(A'_d)} \\
\leq Ch^2(d^{2\beta-2} - d^{\beta-2}) \leq Ch^2d^{\beta-2}.
\]

A slight variation of the usual duality argument, in order to account for the precise dependence on \( d \), gives (see [11, Lemma 5.1] for details)

\[
(2.11) \quad \frac{1}{d}\|\overline{E}_d\|_{L^2(A''_d)} \leq Ch^{\beta-\epsilon}d^{-\beta}\|\overline{E}_d\|_{H^1(\Omega)}.
\]

Next, by (1.3) and (2.2.ii),

\[
(2.12) \quad \|\widetilde{w}_d^1 - P_h\widetilde{w}_d^1\|_{H^r(\Omega)} \leq Ch^{2\beta-\epsilon}\|\widetilde{w}_d^1\|_{H^{3\beta-\epsilon}(\Omega)} \leq Ch^{2\beta-\epsilon}.
\]

Further, by (1.3) and a simple calculation of \( \|\widetilde{w}_d^2\|_{H^2} \),

\[
(2.13) \quad \|\widetilde{w}_d^2 - P_h\widetilde{w}_d^2\|_{H^r(\Omega)} \leq Ch\|\widetilde{w}_d^2\|_{H^2(\Omega)} \leq Chd^{\beta-1}.
\]

Also, by (1.3) and (2.2.iii), we have, with \( \beta' = \min(\beta, R - 1) > \beta \),

\[
(2.14) \quad \|\widetilde{w}_d^2 - P_h\widetilde{w}_d^2\|_{H^r(\Omega)} \leq Ch^{\beta-\epsilon}\|\widetilde{w}_d^2\|_{H^{\beta-\epsilon}(\Omega)} \leq Ch^{\beta-\epsilon}.
\]

Inserting (2.12)–(2.14) into (2.11) gives

\[
\frac{1}{d}\|\overline{E}_d\|_{L^2(A''_d)} \leq C\left(h^{3\beta-\epsilon}d^{-\beta} + h^{1+\beta-\epsilon}d^{-1} + h^{\beta'+\beta-2\epsilon}d^{-\beta}\right).
\]

Using this and (2.10) in (2.9),

\[
\|\overline{E}_d\|_{L^\infty(A_d)} \leq Ch^{-\epsilon}(h^{3\beta-2\epsilon}d^{-2} + h^{3\beta-2\epsilon}d^{-\beta} + h^{1+\beta-\epsilon}d^{-1} + h^{\beta'+\beta-2\epsilon}d^{-\beta}) \\
= Ch^{2\beta-\epsilon}\left(\frac{h}{d}\right)^{2\beta-2\epsilon} + h^{\beta'-\epsilon} + h^{\beta-3\epsilon} + \left(\frac{h}{d}\right)^{1-\beta}h^{-\epsilon} + h^{\beta'-\beta-3\epsilon}.
\]

Since \( h/d \leq h^5 \) and \( \beta' > \beta \), we obtain the desired result (2.7) for \( \epsilon \) small enough.

This completes the proof of Theorem 1.2.

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