CHILD DEVELOPMENT

Child Development, March/April 2014, Volume 85, Number 2, Pages 437–443

Beginnings of Place Value: How Preschoolers Write Three-Digit Numbers

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Place value notation is essential to mathematics learning. This study examined young children's (4- to 6-year-olds, N = 172) understanding of place value prior to explicit schooling by asking them write spoken numbers (e.g., "six hundred and forty-two"). Children's attempts often consisted of "expansions" in which the proper digits were written in order but with 0s or other insertions marking place (e.g., "600402" or "610042"). This partial knowledge increased with age. Gender differences were also observed with older boys more likely than older girls to produce the conventional form (e.g., 642). Potential experiences contributing to expanded number writing and the observed gender differences are discussed.

Piaget (Flavell, 1963) advised developmentalists not to just track children's successes in their progress to conceptual maturity but to study the errors they made along the way. Children's errors in Piaget's balance beam task provide insight into the tensions within the not-quite-right internal algebra through which young children combine different sources of information (Siegler, 1976); children's early use of "goed" for "went" reveals that they represent verbs and their inflections as separate meaningful units and go beyond specific experiences to form a coherent system (Marcus et al., 1992); and children's invented spellings—offerings such as "MITN" for "mitten"—tell us how they represent the sound structure of English and reveal their readiness to form rules that map written letters to sounds (Treiman, 1993). In this study, we invited young children to make errors by asking them to write multidigit numbers with the goal of measuring what children might know about place value notation prior to explicit instruction.

Multidigit Hindu-Arabic numbers instantiate the principle of place value: The value of an individual digit is determined by its position within the number, and the value of the number is determined by the sum of each of these values. Thus, for 642, the 6 means 600, the 4 means 40, and the value is 600 + 40 + 2. Failure to understand place value limits later mathematics learning (Fuson, 1990; Moeller, Pixner, Zuber, Kaufmann, & Nuerk, 2011) and is a stumbling block for many children late into their schooling (Fuson, 1990). The place value system is implicit in spoken numbers ("one hundred and fifty-six"); however, the mapping from spoken to written numbers is not straightforward (Fuson, 1990; Tolchinsky, 2003). Whereas spoken numbers use morphemes ("-ty," "hundred," etc.) to denote units of different size, written numbers use only relative position. Furthermore, a sequence of spoken number words implies an arithmetic relation that may be addition ("one hundred and two," e.g., 100 + 2), multiplication ("three hundred," e.g., 3 × 100), or both ("three hundred and two," e.g., 3 × 100 + 2). In written notation, the underlying structure is more regular: Each digit is multiplied by the corresponding base and the results are summed (e.g., 642 is 6 × 100 + 4 × 10 + 2 × 1). In addition, zeros are omitted in spoken numbers but never in written numbers (e.g., "three hundred and two" vs. 302). As many have noted (see Fuson, 1990; Tolchinsky, 2003), place value notation is a difficult-to-master system and a complicated one.

Prior to schooling, young children see written numbers and hear spoken number names. What might they discern about place value from these informal experiences? One possibility is that children know very little without formal instruction. This seems plausible given the complexity of the notation itself. The alternative possibility, and the one we pursue here, is that young children extract regularities from their incidental experiences of written and spoken forms, and have ideas, perhaps

This research was supported by IES Grant R305A080287 to LBS and KM and an NSF IGERT traineeship to LB. We thank Cody Stitzel for assistance in data collection.

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DOI: 10.1111/cdev.12162

imperfect, about how place value notation works. Consistent with this possibility, one previous study found that preschool children have better memory for well-formed multidigit numbers than non-well-formed numbers (Barrouillet, Thevenot, & Fayol, 2010). Formal instruction must build on or counter children's intuitive knowledge about place value, and thus a description of this early knowledge is a critical open question.

We used a writing task in the present experiment because of previous findings about number writing errors in school-age children. Older children show a characteristic error pattern that goes beyond the mere skipping or inverting of digits in the written string and consists of adding extra digits. That is, when they make mistakes, they typically write the digits in the order in which they heard them, but add extra digits, for example, writing "six hundred and forty-two" as 600402 or 610042 or 6042, or even sometimes as 61412. Different researchers have used different names for these errors (Scheuer, Sinclair, de Rivas, & Tièche-Christinat, 2000; Seron & Fayol, 1994; Tolchinsky, 2003; Zuber, Pixner, Moeller, & Nuerk, 2009); we will refer to the phenomenon as "expanded number writing." In school-age children, expanded number writing is associated with difficulties in mathematics (Moeller et al., 2011).

Is this error a common first understanding of multidigit numbers, and not just a marker of later difficulties in mathematics? Expanded number writing may have its origins in children's early incidental learning about multidigit numbers—based on a mapping between heard and written forms. If this hypothesis is correct, one might see widespread evidence of expanded number writing prior to formal schooling. Consistent with this idea, reports from several clinical-interview studies include examples of expanded number writing in preschoolers (Brizuela & Cayton, 2010; Lerner & Sadovsky, 1994; Scheuer et al., 2000). These reports could reflect the demand characteristics of the interview method or could reflect the first understanding of a few precocious children. Alternatively, they could represent a common informal understanding of the notation system, and thus one that may be resistant to change in some children when explicit instruction begins. We do know that when older children make errors, this is the dominant kind of error they make, and it has been reported across numerous studies spanning multiple countries and languages (Barrouillet, Camos, Perruchet, & Seron, 2004; Brizuela & Cayton, 2010; Camos, 2008; Krinzinger, 2010; Lerner & Sadovsky, 1994; Moeller et al., 2011; Pixner et al., 2011; Power & Dal Martello, 1990; Scheuer et al., 2000; Seron & Fayol, 1994; Zuber et al., 2009). The breadth of this error across languages, cultures, and curricula suggests that it represents a compelling (albeit wrong) idea about how to write large numbers.

This study examined number writing in 4- to 6-year-old children in an effort to capture the possible developmental emergence of expanded number writing. Gender was also included in the analyses because the literature on multidigit number writing in older school-age children includes several mentions of girls producing more number writing errors than boys (Krinzinger, 2010; Pixner et al., 2011; Zuber et al., 2009). Three-digit numbers without internal zeros were chosen as stimuli because they produced the highest rate of expanded number writing among three-digit numbers in older children (Zuber et al., 2009).

Method

Participants

The participants were one hundred and seventy-two 4- to 6-year-olds, forty-one 4-year-olds (24 boys, 17 girls, M_{age} = 52.9 months, range = 48.6–59.8), seventy-two 5-year-olds (35 boys, 37 girls, M_{age} = 65.7 months, range = 60.1–71.9), and fifty-nine 6-year-olds (25 boys, 34 girls, M_{age} = 76.0 months, range = 72.1–83.2). There were no differences in the mean age of boys and girls in any age group. A sample of children representative of Monroe County, Indiana, a predominantly European American (88%; 3% African American, 3% Asian American, 2% Latino, 4% Other) working- and middle-class community (25% below the poverty level), was recruited through community organizations (e.g., museums, child outreach events, girls clubs) and at 12 different day cares serving a diverse population. Most of the 5- and 6-year-olds were in some form of half-day kindergarten (at public school or in day care); kindergarten is not required by the state of Indiana and the curriculum varies considerably across different schools. The local public school kindergarten curriculum does not include the writing of multidigit numbers. The first-grade curriculum includes writing numbers up to 100; 19 children were tested in the fall of first grade and thus may have had exposure to this curriculum.

Stimuli

The stimuli consisted of verbally dictated three-digit numbers. Because nothing was known about how preschoolers might perform in this task, the specific numbers were selected with following general properties: All nine nonzero digits were represented, the position of the largest digit varied, and the set included some numbers that differed only in one or two places. The numbers were presented in the randomly determined order: 642, 459, 274, 437, 875, 945, 578, 592, 974, 358, 651, 653, 517, 451, 693, 854, 846, 873, 782, 184. We chose to use the same order for all participants in case some children were unable to complete the task. The numbers were dictated with the word "and" included but not emphasized; for example, 642 was dictated as "six hundred and forty-two." The goal was to speak the numbers as children usually hear them.

Procedure

Children were tested individually sitting at a table across from the experimenter, in the laboratory or in a private area in their day care. The child was given a pencil and a widely lined sheet of paper. For each trial, the experimenter said: "Can you write *number*?" (e.g., "Can you write six hundred and forty-two?") The experimenter dictated each number twice at a conversational pace (approximately 2 s per number) and was generally affirming of all attempts but provided no specific feedback. If a child was clearly not attending to the dictation (e.g., looking away or talking), the trial was repeated. Children were allowed unlimited time to write the number once they started writing, but if after 20 s the child did not begin writing, the trial was considered a nonresponse and the next trial was started. If after the child completed his or her writing of the number, the written attempt included an ambiguous form (e.g., a circle next to a line in the intended place of a 9, a backward 4), the experimenter pointed to that form and asked the child what it was. If the child answered with a number name, that name was taken as the written digit. Children whose first three responses were scribbling or nonresponses were excused from the remainder of testing. These children's data are included in the overall description of the sample with their responses scored as "other."

Experimental sessions were conducted by six trained research assistants and a graduate student, and were typically completed within 20 min.

Coding

Two coders independently scored 70% of trials, classifying each writing attempt as conventional, expanded, digit strings, or other. Conventional number writing was defined as the correct sequence of digits. An effort was considered an expanded form if it contained all the required digits in order but with extra elements added between them. Efforts that contained digits but did not meet the criteria for conventional or expanded number writing were classified as digit strings. All other responses were classified as other. Patterns of expanded number writing were more specifically coded as including an inserted 0, 1, or 100, sequences of zeros, or sequences including 0s, 1s, or other digits. Reliability was 95% agreement for classifications and 96% agreement for patterns. A third coder was used as a tiebreaker.

Results

Figure 1 shows examples of writing attempts. Table 1 shows the mean proportion of responses as well as the proportion of children, partitioned into three age groups, who produced that form of writing at least once. Conventional number writing was rare in the overall sample but was produced by some 6-year-olds. Expanded number writing increased across the age groups and was the dominant production for 5- and 6-year-olds. Indeed,

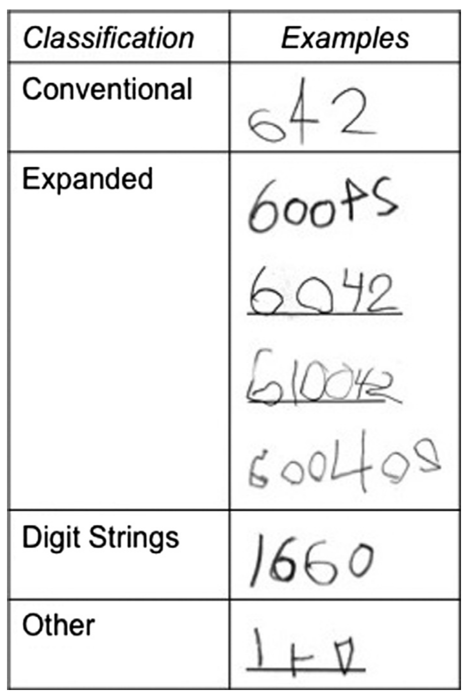

Figure 1. Representative examples of each response type. Expanded productions are ordered by decreasing frequency.

expanded number writing was produced at least once by 76% of the children in the 5-year-old group and 61% of children in the 6-year-old group. Other (nondigit) responses dominated 4-year-olds' attempts. Digit strings were produced at all ages but were not the dominant response for any age group. Overall, the results suggest a period, prior to the mastery of conventional number writing, in which expanded number writing emerges and is common. We first present statistical analyses with respect to the age-related changes in expanded number writing and then with respect to the age-related changes in conventional number writing.

Figure 2 shows the mean proportion of trials on which children produced expanded number writing as a function of age group and gender. Expanded number writing was prevalent in the 5-year-old group (M = .54, SD = .41 of productions for girls; M = .54, SD = .39 of productions for boys) and in the 6-year-old group (M = .58, SD = .45 for girls; M = .34, SD = .42 for boys). The proportions of trials on which expanded number writing was produced were entered into a 3 (age group: 4 vs. 5 vs. 6) × 2 (gender: boy vs. girl) analysis of variance (ANOVA). The analysis yielded a reliable main effect of age group, $F(2, 166) = 18.94$, $p < .001$, partial $\eta^2 = .18$, and a marginal interaction between age and gender, $F(2, 166) = 2.91$, $p = .057$, partial $\eta^2 = .034$. As is evident in Figure 2, this marginal interaction reflects a decrease in expanded number writing by 6-year-old boys relative to 5-year-old boys and 6-year-old girls. A multiple regression with age (in months) and gender as predictors indicated that these predictors jointly explained 14% of the variance in expanded number writing, $R^2 = .14$, $F(3, 168) = 9.17$, $p < .001$. Age significantly predicted expanded number writing, $b = 0.016$, $t(168) = 4.74$, $p < .001$, partial $\eta^2 = .12$, and as mentioned above there was a marginal interaction of age and gender, $b = 0.0060$, $t(168) = 1.81$, $p = .071$, partial $\eta^2 = .019$.

Table 1
Production of Each Response Type by Age Group

Classification	Age 4	Age 5	Age 6
Conventional	.01 (.15)	.06 (.31)	.33 (.41)
Expanded	.10 (.22)	.54 (.76)	.48 (.61)
Digit strings	.19 (.41)	.23 (.82)	.14 (.54)
Other	.70 (.83)	.17 (.18)	.05 (.07)

Note. Values outside parentheses are the mean proportion of trials each response type that was used by all participants at each age group. Values inside parentheses are the proportion of subjects at each age level with at least one response of this type.

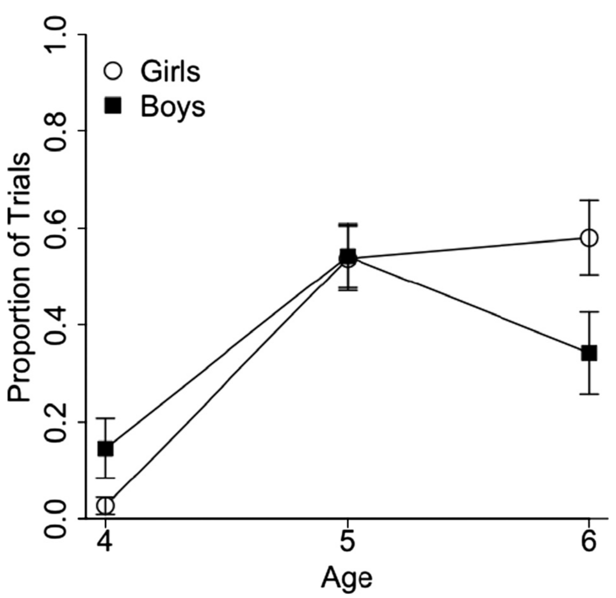

Figure 2. Proportion of trials in which expanded number writing was produced as a function of age group and gender. Error bars depict standard errors of the means.

Children's expansions primarily consisted of adding extra digits after the correct hundreds digit: 97% of all expanded forms for girls and 99% for boys included these additions. The majority of these additions consisted of adding "100," "00," or "0" (84% for girls and 76% for boys). Thus, the character of expanded forms was similar for boys and girls and consisted of added elements in the written form at the location corresponding to where "hundred" is heard in the spoken form.

Correct conventional number writing was rare but as shown in Figure 3 did increase across the three age groups. For the 6-year-old boys, conventional number writing was produced on average .53 of all trials; in contrast, it was produced on only .19 of trials by 6-year-old girls. A 3 (age group: 4 vs. 5 vs. 6) × 2 (gender: boy vs. girl) ANOVA yielded reliable main effects of age group, $F(2, 166) = 26.51$, $p < .001$, partial $\eta^2 = .23$; gender, $F(1, 166) = 7.98$, $p < .01$, partial $\eta^2 = .053$; and a reliable interaction between age group and gender, $F(2, 166) = 7.35$, $p < .001$, partial $\eta^2 = .081$. Post hoc pairwise comparisons (Bonferroni-corrected to $\alpha = .05/7 = .0071$) indicated that 6-year-old boys produced conventional number writing more than 6-year-old girls, $t(57) = 3.08$, $p = .0032$, Cohen's $d = 0.81$, and conventional number writing increased between the 5- and 6-year-old groups for boys, $t(58) = 5.22$, $p < .001$, Cohen's $d = 1.37$, but

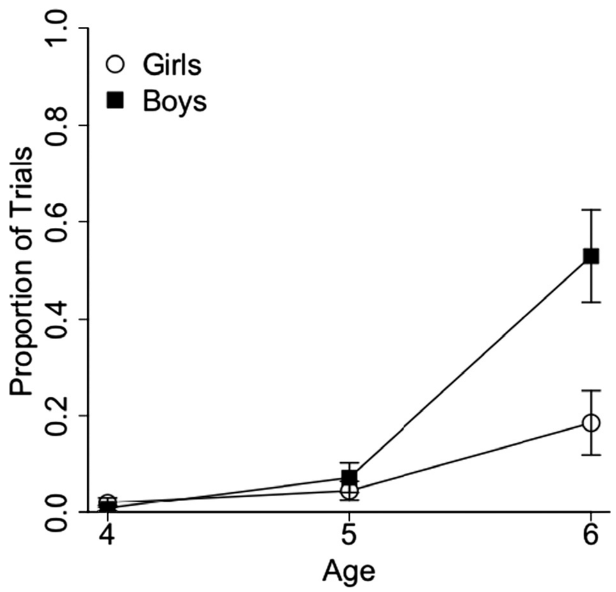

Figure 3. Proportion of trials in which conventional number writing was produced as a function of age group and gender. Error bars depict standard errors of the means.

not for girls, $t(69) = 2.10$, $p = .039$, *ns* after correction. The effect size for the gender difference in conventional number writing at the oldest group, $d = 0.81$, is considered to be large (Hyde, 2005). Because 19 of the 6-year-olds had started first grade, we repeated the above analysis with these children removed; the pattern of results was unchanged including the interaction between age group and gender, $F(2, 147) = 5.86$, $p < .01$, partial $\eta^2 = .074$. A multiple regression with age (in months) and gender as predictors indicated that these predictors jointly explained 23% of the variance in conventional number writing, $R^2 = .23$, $F(3, 168) = 17.02$, $p < .001$. All variables significantly predicted conventional number writing: age, $b = 0.014$, $t(168) = 6.18$, $p < .001$, partial $\eta^2 = .19$; gender, $b = 0.36$, $t(168) = 2.32$, $p < .05$, partial $\eta^2 = .041$; and the interaction of age and gender, $b = -0.0062$, $t(168) = -2.71$, $p < .01$, partial $\eta^2 = .042$.

We could find no easy explanation of these gender differences in terms of the sample of children who participated. Equal numbers of boys and girls were tested in the laboratory—35/84 boys versus 40/88 girls, $\chi^2(1) = 0.12$, $p = .73$, *ns*, versus in local day cares, and a Fisher's exact test of the distributions of boys and girls across the 12 individual day cares revealed no reliable gender differences across testing locations ($p = .55$, *ns*). Furthermore, no location (laboratory or specific day care) was overrepresented with respect to the children (mostly boys) who produced conventional number writing at least 50% of the time (Fisher's exact test, $p = .40$, *ns*).

In summary, the results indicate that expanded number writing is common in young children and emerges prior to explicit training about the place value system. The results also indicate gender differences that interacted with age; the oldest boys were much more likely to produce conventional correct forms than were same-aged girls. However, when considered as the proportion of nonconventional forms produced by the children, the frequency of expanded number writing did not differ between boys and girls, .45 for boys vs. .50 for girls; $t(156) = 0.71$, $p = .48$, *ns*, and thus appears the common form of error for both boys and girls.

Discussion

Children's additions of zeros or the unit 100 suggest that they are trying to align spoken names to the written forms, perhaps under an assumption that "two hundred and fifty-four" requires explicit written notation of "hundred." Clearly, young children are not merely reproducing the specific multidigit numbers they have seen but instead are generating a written form based on their own ideas about how number writing might work and partial knowledge about that system. The children in this study knew that the first digit mentioned gets written on the left, the second mentioned gets written in the middle, and the third mentioned gets written on the right—a rule from which there was very little deviation. This correct temporal-spatial pattern seems likely to emerge from the mapping of heard number names to seen digits. However, the heard sounds have components with no correspondence in the written forms, and thus children's written additions may indicate an attempt to map each heard unit to a corresponding written unit.

Children's expanded number writing might also reflect statistical regularities across frequently heard and seen numbers. Across all their incidental experiences of written and spoken forms, young children are likely to have noticed the cases in which the spoken and written do correspond (e.g., "one hundred" and 100) and to have noticed that "big" numbers are verbally marked by the word "hundred" and often include zeros. Furthermore, analyses of the frequencies of written numbers in text indicate that certain "benchmark" numbers are much more frequent than others (Dehaene & Mehler, 1992); thus, children are likely to have experienced the written forms of these benchmarks more than other numbers—100 more than 125, 500 more than 586, 800 more than 872. Young children's productions, then, might reflect the statistical aggregation of many-to-many mappings of number names to written forms, with frequently experienced written forms weighted more heavily. Some interpretations of expanded number writing in school-age children posit an overreliance on heard number names (Pixner et al., 2011; Zuber et al., 2009) because expanded productions seem to preserve the structure in the heard form at the expense of position or place in the written form. We hypothesize that this seeming overreliance may reflect the statistical structure of children's early experienced mappings between written and spoken forms.

Expanded number writing by school-age children has been linked to a poor understanding of place value and poor performance in mathematics (Moeller et al., 2011). However, the negative relation could concern expanded number writing that persists in the face of explicit instruction. Just as the idiosyncratic invented spellings of young children predict reading readiness but the persistence of this form of spelling in school may be associated with poor reading ability (Treiman, 1993), early efforts at expanded number writing may be positive indicators of the child's engagement with spoken and written forms and sensitivity to the structural regularities in number notation. Pertinent to this point, school curricula for teaching place value often include tasks that ask children to expand multidigit numbers, for example, to write "541" as "500 + 40 + 1" (Common Core State Standards Initiative, 2010). The expanded forms of preschoolers appear to be at least part way there, indicating knowledge of the left-to-right order of 100s, 10s, and 1s, the role of "0" in marking place, and perhaps most importantly the compositional structure of multidigit numbers (see also Tolchinsky, 2003). Clearly an important next step is to determine whether expanded number writing before explicit instruction predicts better later learning given explicit instruction.

The present findings provide strong evidence for the prevalence of expanded number writing in a large sample of children. However, in the present sample, older boys were more likely than same-aged girls to produce correct conventional number writing. In the literature on older children's writing of multidigit numbers, several studies have reported that school-age girls produce more errors than boys (Krinzinger, 2010; Pixner et al., 2011; Zuber et al., 2009). The gender differences reported in the multidigit number writing of older children could be related to the gender differences observed here and be markers of an early advantage for boys in learning about place value (Gibbs, 2010). Alternatively, if expanded number writing is a sign of early engagement, analysis, and rerepresentation of multidigit numbers (as in the manner proposed by Karmiloff-Smith in other domains; Karmiloff-Smith & Inhelder, 1974), then girls' persistence could be interpreted as reflecting deeper analysis and understanding.

Finding gender-specific differences does not indicate their cause (Hyde, 2005), and there are several possible sources of the gender differences observed in this study. One recent analysis of parent speech to 2-year-olds indicated more number-related input to boys than to girls (Chang, Sandhofer, & Brown, 2011). However, for more talk about numbers to matter for the observed gender differences, that talk needs to be about multidigit numbers in the context of the written representation of those numbers. As far as we know, this possibility has not been examined by anyone. It is also possible that boys and girls process their experiences (be they similar or different) in different ways. More specifically, there is evidence—from both children and adults—to suggest that male participants and female participants differentially weight the evidence from heard words and visual forms, with female participants emphasizing what is heard more than what is seen (Coltheart, Hull, & Slater, 1975; Hood, 2004; Huestegge, Heim, Zettelmeyer, & Lange-Küttner, 2011; Wolf & Gow, 1985–1986), an emphasis that may lead to more persistence, prior to explicit instruction, in attempts to align the heard names with written strings. If this is so, then boys and girls might follow somewhat different paths in learning about place value. However, as Gibbs (2010) remarked, gender-specific developmental pathways and systems for mathematics understanding need not mean differences in ultimate performance (see also Bull, Cleland, & Mitchell, 2013).

In conclusion, many young children willingly attempt to write multidigit numbers before explicit instruction about place value and their generative attempts illustrate knowledge—albeit imperfect—about multidigit numbers that appear to be leveraged from the structure of spoken number names and their experiences with written number forms. The frequency of expanded number writing in the 5- and 6-year-olds in this study supports the idea that it is the typical first approach to understand place value and therefore a potential foundation on which formal instruction might begin.

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