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$$\frac{\rho_j V_j^2}{R_j} = \frac{\rho_{amb} V_g^2}{R_{amb}}$$

where R_j is the radius of curvature of the jet, ρ_{amb} is the density of the medium surrounding the jet, V_g is the galaxy velocity, and R_{amb} is the pressure scale height over which the ram pressure is effective. However, the numerical results might be affected by the large numerical viscosity inherent in De Young's code.
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Rules of Language

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Language and cognition have been explained as the products of a homogeneous associative memory structure or alternatively, of a set of genetically determined computational modules in which rules manipulate symbolic representations. Intensive study of one phenomenon of English grammar and how it is processed and acquired suggests that both theories are partly right. Regular verbs (*walk-walked*) are computed by a suffixation rule in a neural system for grammatical processing; irregular verbs (*run-ran*) are retrieved from an associative memory.

EVERY NORMAL HUMAN CAN CONVEY AND RECEIVE AN unlimited number of discrete messages through a highly structured stream of sound or, in the case of signed languages, manual gestures. This remarkable piece of natural engineering depends upon a complex code or grammar implemented in the brain that is deployed without conscious effort and that develops, without explicit training, by the age of four. Explaining this talent is an important goal of the human sciences.

Theories of language and other cognitive processes generally fall into two classes. Associationism describes the brain as a homogeneous network of interconnected units modified by a learning mechanism that records correlations among frequently co-occurring input patterns (*1*). Rule-and-representation theories describe the brain as a computational device in which rules and principles operate on symbolic data structures (*2, 3*). Some rule theories further propose that the brain is divided into modular computational systems that have an organization that is largely specified genetically, one of the systems being language (*3, 4*).

During the last 35 years, there has been an unprecedented empirical study of human language structure, acquisition, use, and breakdown, allowing these centuries-old proposals to be refined and tested. I will illustrate how intensive multidisciplinary study of one linguistic phenomenon shows that both associationism and rule theories are partly correct, but about different components of the language system.

Modules of Language

A grammar defines a mapping between sounds and meanings, but the mapping is not done in a single step but through a chain of intermediate data structures, each governed by a subsystem. Morphology is the subsystem that computes the forms of words. I focus on a single process of morphology: English past tense inflection, in which the physical shape of the verb varies to encode the relative time of occurrence of the referent event and the speech act. Regular

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past tenses marking (for example, *walk-walked*) is a rulelike process resulting in addition of the suffix *-d*. In addition there are about 180 irregular verbs that mark the past tense in other ways (for example, *hit-hit, come-came, feel-felt*).

Past tense inflection is an isolable subsystem in which grammatical mechanisms can be studied in detail, without complex interactions with the rest of language. It is computed independently of syntax, the subsystem that defines the form of phrases and sentences: The syntax of English forces its speakers to mark tense in every sentence, but no aspect of syntax works differently with regular and irregular verbs. Past tense marking is also insensitive to lexical semantics (*5, 6*): the regular-irregular distinction does not correlate with any feature of verb meaning. For example, *hit-hit, strike-struck,* and *slap-slapped* have similar meanings, but three different past tense forms; *stand-stood, stand me up–stood me up,* and *understand-understood,* have unrelated meanings but identical past tense forms. Past marking is also independent of phonology, which determines the possible sound sequences in a language: the three pronunciations of the regular suffix (in *ripped, ribbed,* and *ridded*) represent not three independent processes but a single suffix *-d* modified to conform with general laws of English sound patterning (*5*).

Rulelike Processes in Language

English inflection can illustrate the major kinds of theories used to explain linguistic processes. Traditional grammar offers the following first approximation: Regular inflection, being fully predictable, is computed by a rule that concatenates the affix *-d* to the verb stem. This allows a speaker to inflect an unlimited number of new verbs, an ability seen both in adults, who easily create past forms for neologisms like *faxed,* and in preschoolers, who, given a novel verb like *to rick* in experiments, freely produced *ricked* (*7*). In contrast, irregular verb forms are unpredictable: compare *sit-sat* and *hit-hit, sing-sang* and *string-strung, feel-felt* and *tell-told.* Therefore they must be individually memorized. Retrieval of an irregular form from memory ordinarily blocks application of the regular rule, although in children retrieval occasionally fails, yielding "overregularization" errors like *breaked* (*8, 9, 10*).

The rule-rote theory, although appealingly straightforward, is inadequate. Rote memory, if thought of as a list of slots, is designed for the very rare verbs with unrelated past tense forms, like *be-was* and *go-went.* But for all other irregular verbs, the phonological content of the stem is largely preserved in the past form, as in *swing-swung* (*5, 11*). Moreover, a given irregular pattern such as a vowel change is typically seen in a family of phonetically similar items, such as *sing-sang, ring-rang, spring-sprang, shrink-shrank,* and *swim-swam,* or *grow-grew, blow-blew, throw-threw,* and *fly-flew* (*5, 9, 11*). The rote theory cannot explain why verbs with irregular past forms come in similarity families, rather than belonging to arbitrary lists. Finally, irregular pairs are psychologically not a closed list, but their patterns can sometimes be extended to new forms on the basis of similarity to existing forms. All children occasionally use forms such as *bring-brang* and *bite-bote* (*5, 9*). A few irregular past forms have entered the language historically under the influence of existing forms. *Quit, cost, catch* are from French, and *fling, sling, stick* have joined irregular clusters in the last few hundred years (*12*); such effects are obvious when dialects are compared [for example, *help-holp, rise-riz, drag-drug, climb-clome* (*13*)]. Such analogizing can be demonstrated in the laboratory: faced with inflecting nonsense verbs like *spling,* many adults produce *splung* (*6, 7, 14, 15*).

The partial systematicity of irregular verbs has been handled in opposite ways by modern rule and associationist theories. One version of the theory of Generative Phonology (*11*) posits rules for irregular verbs (for example, change *i* to *a*) as well as for regular ones. The theory is designed to explain the similarity between verb stems and their past tense forms: if the rule just changes a specified segment, the rest of the stem comes through in the output untouched, by default, just as in the fully regular case. But the rule theory does not address the similarity among different verbs in the input set and people's tendency to generalize irregular patterns. If an irregular rule is restricted to apply to a list of words, the similarity among the words in the list is unexplained. But if a common pattern shared by the words is identified and the rule is restricted to apply to all and only the verbs displaying that pattern (for example, change *i* to *a* when it appears after an consonant cluster and precedes *ng*), the rule fails because the similarity to be accounted for is one of family resemblance rather than necessary or sufficient conditions (*5, 9, 14, 18*): such a rule, while successfully applying to *spring, shrink, drink,* would incorrectly apply to *bring-brought* and *fling-flung* and would fail to apply to *begin-began* and *swim-swam,* where it should apply.

Associationist theories also propose that regular and irregular patterns are computed by a single mechanism, but here the mechanism is an associative memory. A formal implementation in neural net terms is the "connectionist" model of Rumelhart and McClelland (*16*), which consists of an array of input units, an array of output units, and a matrix of modifiable weighted links between every input and every output. None of the elements or links corresponds exactly to a word or rule. The stem is represented by turning on a subset of input nodes, each corresponding to a sound pattern in the stem. This sends a signal across each of the links to the output nodes, which represent the sounds of the past tense form. Each output node sums its incoming signals and turns on if the sum exceeds a threshold; the output form is the word most compatible with the set of active output nodes. During the learning phase, the past tense form computed by the network is juxtaposed with the correct version provided by a "teacher," and the strengths of the links and thresholds are adjusted so as to reduce the difference. By recording and superimposing associations between stem sounds and past sounds, the model improves its performance and can generalize to new forms to the extent that their sounds overlap with old ones. This process is qualitatively the same for regular and irregular verbs: *stopped* is produced because input *op* units were linked to output *opped* units by previous verbs; *clung* is produced because *ing* was linked to *ung.* As a result such models can imitate people's analogizing of irregular patterns to new forms.

The models, however, are inadequate in other ways (*5, 17*). The precise patterns of inflectional mappings in the world's languages are unaccounted for: the network can learn input-output mappings found in no human language, such as mirror-reversing the order of segments, and cannot learn mappings that are common, such as reduplicating the stem. The actual outputs are often unsystematic blends such as *mail-membled* and *tour-tourder.* Lacking a representation of words as lexical entries, distinct from their phonological or semantic content, the model cannot explain how languages can contain semantically unrelated homophones with different past tense forms such as *lie-lied* (prevaricate) and *lie-lay* (recline), *ring-rang* and *wring-wrung, meet-met* and *mete-meted.*

These problems call for a theory of language with both a computational component, containing specific kinds of rules and representations, and an associative memory system, with certain properties of connectionist models (*5, 6, 10*). In such a theory, regular past tense forms are computed by a rule that concatenates an affix with a variable standing for the stem. Irregulars are memorized pairs of words, but the linkages between the pair members are stored in an associative memory structure fostering some generalization by analogy (*9, 14, 18*): although *string* and *strung* are represented as separate, linked words, the mental representation of the pair overlaps in part with similar forms like *sling* and *bring*, so that the learning of *slung* is easier and extensions like *brung* can occur as the result of noise or decay in the parts of the representation that code the identity of the lexical entry.

Because it categorically distinguishes regular from irregular forms, the rule-association hybrid predicts that the two processes should be dissociable from virtually every point of view. With respect to the psychology of language use, irregular forms, as memorized items, should be strongly affected by properties of associative memory such as frequency and similarity, whereas regular forms should not. With respect to language structure, irregular forms, as memory-listed words, should be available as the input to other word-formation processes, whereas regular forms, being the final outputs of such processes, should not. With respect to implementation in the brain, because regular and irregular verbs are subserved by different mechanisms, it should be possible to find one system impaired while the other is spared. The predictions can be tested with methods ranging from reaction time experiments to the grammatical analysis of languages to the study of child development to the investigation of brain damage and genetic deficits.

Language Use and Associative Laws

Frequency. If irregular verbs are memorized items, they should be better remembered the more they are encountered. Indeed, children make errors like *breaked* more often for verbs their parents use in the past tense forms less frequently (*9, 10, 19*). To adults, low-frequency irregular past tense forms like *smote, bade, slew*, and *strode* sound odd or stilted and often coexist with regularized counterparts such as *slayed* and *strided* (*5, 18, 20*). As these psychological effects accumulate over generations, they shape the language. Old English had many more irregular verbs than Modern English, such as *abide-abode, chide-chid, gild-gilt*; the ones used with lower frequencies have become regular over the centuries (*18*). Most surviving irregular verbs are used at high frequencies, and the 13 most frequent verbs in English—*be, have, do, say, make, go, take, come, see, get, know, give, find*—are all irregular (*21*).

Although any theory positing a frequency-sensitive memory can account for frequency effects on irregular verbs [with inverse effects on their corresponding regularized versions (20)], the rule-associative-memory hybrid model predicts that regular inflection is different. If regular past tense forms can be computed on-line by concatenation of symbols for the stem and affix, they do not require prior storage of a past tense entry and thus need not be harder or stranger for low-frequency verbs than higher ones (*22*).

Judgments by native English speakers of the naturalness of word forms bear this prediction out. Unlike irregular verbs, novel or low-frequency regular verbs, although they may sound unfamiliar in themselves, do not accrue any increment of oddness or uncertainty when put in the past tense: *infarcted* is as natural a past tense form of *infarct* as *walked* is of *walk* (*5*). The contrast can be seen clearly in idioms and clichés, because they can contain a verb that is not unfamiliar itself but that appears in the idiom exclusively in the present or infinitive form. Irregular verbs in such idioms can sound strange when put in the past tense: Compare *You'll excuse me if I forgo the pleasure of reading your paper before it's published* with *Last night I forwent the pleasure of reading student papers*, or *I don't know how she can bear the guy* with *I don't know how she bore the guy*. In contrast, regular verbs in nonpast idioms do not sound worse when put in the past: compare *She doesn't suffer fools gladly* with *None of them ever suffered fools gladly*. Similarly, some regular verbs like *afford* and *cope* usually appear with *can't*, which requires the stem form, and hence have common stems but very low-frequency past tense forms (*21*). But the uncommon *I don't know how he afforded it (coped)* does not sound worse than *He can't afford it (cope)*.

These effects can be demonstrated in quantitative studies (*20*): Subjects' ratings of regular past tense forms of different verbs correlate significantly with their ratings of the corresponding stems ($r = 0.62$) but not with the frequency of the past form (-0.14, partialing out stem rating). In contrast, ratings of irregular past tense forms correlate less strongly with their stem ratings (0.32), and significantly with past frequency (0.29, partialing out stem rating).

Experiments on how people produce and comprehend inflected forms in real time confirm this difference. When subjects see verb stems on a screen and must utter the past form as quickly as possible, they take significantly less time (16- to 29-msec difference) for irregular verbs with high past frequencies than irregular verbs with low past frequencies (stem frequencies equated), but show no such difference for regular verbs (<2-msec difference) (*23*). When recognizing words, people are aided by having seen the word previously on an earlier trial in the experiment; their mental representation of the word has been "primed" by the first presentation. Presenting a regular past tense form speeds up subsequent recognition of the stem no less than presenting the stem itself (181- versus 166-msec reduction), suggesting that people store and prime only the stem and analyze a regular inflected form as a stem plus a suffix. In contrast, prior presentation of an irregular form is significantly less effective at priming its stem than presentation of the stem itself (39- versus 99-msec reduction), suggesting that the two are stored as separate but linked items (*24*).

Similarity. Irregular verbs fall into families with similar stems and similar past tense forms, partly because the associative nature of memory makes it easier to memorize verbs in such families. Indeed, children make fewer overregularization errors for verbs that fall into families with more numerous and higher frequency members (*5, 8–10, 25*). As mentioned above, speakers occasionally extend irregular patterns to verbs that are highly similar to irregular families (*brang*), and such extensions are seen in dialects (*13*). A continuous effect of similarity has been measured experimentally: subjects frequently (44%) convert *spling* to *splung* (based on *string, sling*, et cetera), less often (24%) convert *shink* to *shunk*, and rarely (7%) convert *sid* to *sud* (*14*).

The rule-associative-memory theory predicts that the ability to generate regular past tense forms should not depend on similarity to existing regular verbs: The regular rule applies as a default, treating all nonirregular stems as equally valid instantiations of the mental symbol "verb." Within English vocabulary, we find that a regular verb can have any sound pattern, rather than falling into similarity clusters that complement the irregulars (*5*): for example, *need-needed* coexists with *bleed-bled* and *feed-fed, blink-blinked* with *shrink-shrank* and *drink-drank*. Regular-irregular homophones such as *lie-lay;lie-lied, meet-met;mete-meted*, and *hang-hung;hang-hanged* are the clearest examples. Moreover verbs with highly unusual sounds are easily provided with regular pasts. Although no English verb ends in *-ev* or a neutral vowel (*21*), novel verbs with these patterns are readily inflectable as natural past tense forms, such as *Yeltsin out-Gorbachev'ed Gorbachev* or *We rhumba'd all night*. Children are no more likely to overregularize an irregular verb if it resembles a family of similar regular verbs than if it is dissimilar from regulars, suggesting that regulars, unlike irregulars, do not form attracting clusters in memory (*10, 25*). Adults, when provided with novel verbs, do not rate regular past forms of unusual sounds like *ploamphed* as any worse, relative to the stem, than familiar sounds like *plipped* (similar to *clip, flip, slip*, et cetera), unlike their ratings for irregulars (*15, 26*). In contrast, in associationist models both irregular and regular generalizations tend to be sensitive to similarity. For example the Rumelhart-McClelland model could not produce any output for many novel regular verbs that did not resemble other regulars in the training set (*5, 15, 17*).

Organization of Grammatical Processes

Grammars divide into fairly autonomous submodules in which blocks of rules produce outputs that serve (or cannot serve) as the input for other blocks of rules. Linguistic research suggests an information flow of lexicon to derivational morphology (complex word-formation) to regular inflection, with regular and irregular processes encapsulated within different subcomponents (*27, 28*). If irregular past tense forms are stored in memory as entries in the mental lexicon, then like other stored words they should be the input to rules of complex word formation. If regular past tense forms are computed from words by a rule acting as a default, they should be formed from the outputs of complex word formation rules. Two phenomena illustrate this organization.

A potent demonstration of the earlier point that regular processes can apply to any sound whatsoever, no matter how tightly associated with an irregular pattern, is "regularization-through-derivation": verbs intuitively perceived as derived from nouns or adjectives are always regular, even if similar or identical to an irregular verb. Thus one says *grandstanded*, not *grandstood; flied out* in baseball [from a fly (ball)], not *flew out; high-sticked* in hockey, not *high-stuck* (*5, 6, 28*). The explanation is that irregularity consists of a linkage between two word roots, the atomic sound-meaning pairings stored in the mental lexicon; it is not a link between two words or sound patterns directly. *High-stuck* sounds silly because the verb is tacitly perceived as being based on the noun root (*hockey*) *stick*, and noun roots cannot be listed in the lexicon as having any past tense form (the past tense of a noun makes no sense semantically), let alone an irregular one. Because its root is not the verb *stick* there is no data pathway by which *stuck* can be made available; to obtain a past tense form, the speaker must apply the regular rule, which serves as the default. Subjects presented with novel irregular-sounding verbs (for example, *to line-drive*) strongly prefer the regular past tense form (*line-drived*) if it is understood as being based on a noun ("to hit a line drive"), but not in a control condition for unfamiliarity where the items were based on existing irregular verbs ("to drive along a line"); here the usual irregular form is preferred (*6*).

The effect, moreover, occurs in experiments testing subjects with no college education (*6*) and in preschool children (*29*). This is consistent with the fact that many of these lawful forms entered the language from vernacular speech and were opposed by language mavens and guardians of "proper" style (*6, 13*). "Rules of grammar" in the psycholinguists' sense, and their organization into components, are inherent to the computational systems found in all humans, not just those with access to explicit schooling or stylistic injunctions. These injunctions, involving a very different sense of "rule" as something that ought to be followed, usually pertain to minor differences between standard written and nonstandard spoken dialects.

A related effect occurs in lexical compounds, which sound natural when they contain irregular noun plurals, but not regular noun plurals: Compare *mice-infested* with *rats-infested, teethmarks* with *clawsmarks, men-bashing* with *guys-bashing* (*28*). Assume that this compounding rule is fed by stored words. Irregulars are stored words, so they can feed compounding; regulars are computed at the output end of the morphology system, not stored at the input end, so they do not appear inside lexical compounds. This constraint has been documented experimentally in 3- to 5-year-old children (*30*): when children who knew the word *mice* were asked for a word for a "monster who eats mice," they responded with *mice-eater* 90% of the time; but when children who knew *rats* were asked for a word for "monster who eats rats," they responded *rats-eater* only 2% of the time. The children could not have learned the constraint by recording whether adults use irregular versus regular plurals inside compounds. Adults do not use such compounds often enough for most children to have heard them: the frequency of English compounds containing any kind of plural is indistinguishable from zero (*21, 30*). Rather, the constraint may be a consequence of the inherent organization of the children's grammatical systems.

Developmental and Neurological Dissociations

If regular and irregular patterns are computed in different subsystems, they should dissociate in special populations. Individuals with undeveloped or damaged grammatical systems and intact lexical memory should be unable to compute regular forms but should be able to handle irregulars. Conversely, individuals with intact grammatical systems and atypical lexical retrieval should handle regulars properly but be prone to overregularizing irregulars. Such double dissociations, most clearly demonstrated in detailed case studies, are an important source of evidence for the existence of separate neural subsystems. Preliminary evidence suggests that regular and irregular inflection may show such dissociations.

Children. Most of the grammatical structure of English develops rapidly in the third year of life (*31*). One conspicuous development is the appearance of overregularizations like *comed*. Such errors constitute a worsening of past marking with time; for months beforehand, all overtly marked irregular past forms are correct (*10*). The phenomenon is not due to the child becoming temporarily overwhelmed by the regular pattern because of an influx of regular verbs, as connectionist theories (*16*) predict (*5, 10, 32*). Instead it accompanies the appearance of the regular tense marking process itself: overregularizations appear when the child ceases using bare stems like *walk* to refer to past events (*8, 10*). Say memorization of verb forms from parental speech, including irregulars, can take place as soon as words of any kind can be learned. But deployment of the rule system must await the abstraction of the English rule from a set of word pairs juxtaposed as nonpast and past versions of the same verb. The young child could possess memorized irregulars, produced probabilistically but without overt error, but no rule; the older child, possessing the rule as well, would apply it obligatorily in past tense sentences whenever he failed to retrieve the irregular, resulting in occasional errors.

Aphasics. A syndrome sometimes called agrammatic aphasia can occur after extensive damage to Broca's area and nearby structures in the left cerebral hemisphere. Labored speech, absence of inflections and other grammatical words, and difficulty comprehending grammatical distinctions are frequent symptoms. Agrammatics have trouble reading aloud regular inflected forms: *smiled* is pronounced as *smile, wanted* as *wanting*. Nonregular plural and past forms are read with much greater accuracy, controlling for frequency and pronounceability (*33*). This is predicted if agrammatism results from damage to neural circuitry that executes rules of grammar, including the regular rule necessary for analyzing regularly inflected stimuli, but leaves the lexicon relatively undamaged, including stored irregulars which can be directly matched against the irregular stimuli.

Specific language impairment (SLI). SLI refers to a syndrome of language deficits not attributable to auditory, cognitive, or social problems. The syndrome usually includes delayed onset of language, articulation difficulties in childhood, and problems in controlling grammatical features such as tense, number, gender, case, and person. One form of SLI may especially impair aspects of the regular inflectional process (*34*). Natural speech includes errors like "We're go take a bus; I play musics; One machine clean all the two arena." In experiments, the patients have difficulty converting present sentences to past (32% for SLI; 78% for sibling controls.) The difficulty is more pronounced for regular verbs than irregulars. Regular past forms are virtually absent from the children's spontaneous speech and writing, although irregulars often appear. In the writing samples of two children examined quantitatively, 85% of irregular pasts but 30% of regular pasts were correctly supplied. The first written regular past tense forms are for verbs with past tense frequencies higher than their stem frequencies; subsequent ones are acquired one at a time in response to teacher training, with little transfer to nontrained verbs. Adults' performance improves and their speech begins to sound normal but they continue to have difficulty inflecting nonsense forms like *zoop* (47% for SLI; 83% for controls). It appears as if their ability to apply inflectional rules is impaired relative to their ability to memorize words: irregular forms are acquired relatively normally, enjoying their advantage of high frequencies; regular forms are memorized as if they were irregular.

SLI appears to have an inherited component. Language impairments have been found in 3% of first-degree family members of normal probands but 23% of language-impaired probands (*35*). The impairment has been found to be 80% concordant in monozygotic twins and 35% concordant in dizygotic twins (36). One case study (*34*) investigated a three-generation, 30-member family, 16 of whom had SLI; the syndrome followed the pattern of a dominant, fully penetrant autosomal gene. This constitutes evidence that some aspects of use of grammar have a genetic basis.

Williams syndrome. Williams syndrome (WS), associated with a defective gene expressed in the central nervous system involved in calcium metabolism, causes an unusual kind of mental retardation (*37*). Although their Intelligence Quotient is measured at around 50, older children and adolescents with WS are described as hyperlinguistic with selective sparing of syntax, and grammatical abilities are close to normal in controlled testing (*37*). This is one of several kinds of dissociation in which language is preserved despite severe cognitive impairments, suggesting that the language system is autonomous of many other kinds of cognitive processing.

WS children retrieve words in a deviant fashion (*37*). When normal or other retarded children are asked to name some animals, they say *dog, cat, pig*; WS children offer *unicorn, tyrandon, yak, ibex*. Normal children speak of *pouring water*; WS children speak of *evacuating a glass*. According to the rule-associative-memory hybrid theory, preserved grammatical abilities and deviant retrieval of high-frequency words are preconditions for overregularization. Indeed, some WS children overregularize at high rates (16%), one of their few noticeable grammatical errors (*37, 39*).

Conclusion

For hundreds of years, the mind has been portrayed as a homogeneous system whose complexity comes from the complexity of environmental correlations as recorded by a general-purpose learning mechanism. Modern research on language renders such a view increasingly implausible. Although there is evidence that the memory system used in language acquisition and processing has some of the properties of an associative network, these properties do not exhaust the computational abilities of the brain. Focusing on a single rule of grammar, we find evidence for a system that is modular, independent of real-world meaning, nonassociative (unaffected by frequency and similarity), sensitive to abstract formal distinctions (for example, root versus derived, noun versus verb), more sophisticated than the kinds of "rules" that are explicitly taught, developing on a schedule not timed by environmental input, organized by principles that could not have been learned, possibly with a distinct neural substrate and genetic basis.

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26. Twenty-four subjects read 60 sentences containing novel verbs, presented either in stem form, a past form displaying an English irregular vowel change, or a past form containing the regular suffix. Each subject rated how good the verb sounded with a 7-point scale; each verb was rated in each of the forms by different subjects. For novel verbs highly similar to an irregular family, the irregular past form was rated 0.8 points worse than the stem; for novel verbs dissimilar to the family, the irregular past form was rated 2.2 points worse. For novel verbs resembling a family of regular verbs, the regular past form was rated 0.4 points better than the stem; for novel verbs dissimilar to the family, the regular past form was rated 1.5 points

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Research Article

Occurrence of Earth-Like Bodies in Planetary Systems

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Present theories of terrestrial planet formation predict the rapid "runaway formation" of planetary embryos. The sizes of the embryos increase with heliocentric distance. These embryos then merge to form planets. In earlier Monte Carlo simulations of the merger of these embryos it was assumed that embryos did not form in the asteroid belt, but this assumption may not be valid. Simulations in which runaways were allowed to form in the asteroid belt show that, although the initial distributions of mass, energy, and angular momentum are different from those observed today, during the growth of the planets these distributions spontaneously evolve toward those observed, simply as a result of known solar system processes. Even when a large planet analogous to "Jupiter" does not form, an Earth-sized planet is almost always found near Earth's heliocentric distance. These results suggest that occurrence of Earth-like planets may be a common feature of planetary systems.

According to currently fashionable theory, the growth of the solid planets of our solar system began by accumulation of the dust contained in a primordial circumstellar solar nebula to form a large number of small planetesimals (*1*). After the size of the planetesimals reached 1 to 10 km their further growth was controlled by collisional and gravitationally dominated interactions between one another. Recent studies of this stage of planetesimal growth have concluded that, in the region of the terrestrial planets, planetesimals grew in 10^4 to 10^5 years to form planetary embryos of the size of the moon to Mercury by a process of runaway accumulation (*2*). The final stage of solid planet formation then consisted of the collisional merger of the embryos to form the planets observed today. During this final stage of growth, the mutual gravitational perturbations of the growing planetesimals caused their relative velocities to increase to over 5 km s^{-1}. This increase caused their growth rates to decrease, and as a result the time scale for terrestrial planets to grow to nearly their present sizes was $\sim 10^8$ years.

Two-dimensional (*3*) and three-dimensional (*4*) simulations of the final stage of growth seem to explain a number of features of the observed terrestrial planets. In these earlier model simulations, in order to match the angular momentum and energy of the model to the observed planets, it was assumed that the planetesimals were initially confined within a narrow band, about 0.5 AU (astronomical units) in width, that was smaller in radial extent than the orbits of observed terrestrial planets. In the context of a more general model of solar system formation, this restriction of planetesimals to a narrow band seems artificial. On the other hand, a simple extension of the original distribution to include the region beyond about 1.1 AU led to disagreement with the observations that there are no bodies more massive than $\sim 10^{24}$ g in the asteroid belt and that the total asteroidal mass is small. It also failed to explain why Mars is smaller than Earth and Venus.

In order to proceed further, additional physical mechanisms are required. One such possible explanation of the observations is that rapid growth of Jupiter into a massive planet in $\sim 10^6$ years caused gravitational perturbations sufficiently strong to rapidly pump up the relative velocities of the planetesimals beyond the orbit of Earth to ~ 100 m s^{-1}. Such velocities could preclude the runaway growth of embryos in the part of the solar system between Earth and Jupiter and limit the growth of the asteroids to objects $\lesssim 10^{24}$ g in mass.

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