Since the beginning of our profession, foundation engineers have tried to develop better methods of predicting the axial resistance of piles with only limited success. New and more sophisticated in-situ test methods have been developed, and even complicated computer models have been tried but load test results invariably provide surprises. Although the problem seems relatively simple, the actual condition and state of stress in the soil around a pile after installation involves a complex series of time-dependent changes in the ground associated with the pile installation. Subtle variations in the soil grain size distribution and the pile installation technique can have profound implications (especially with drilled foundations). Since the effects of pile installation are so different between driven and drilled foundations, it is important to understand, at least qualitatively, what happens in the ground and at the pile/soil interface during pile installation.
FEATURE

This article provides a brief review of some of the fundamental aspects of the behavior of drilled and driven piles during installation and the effects of the pile installation methods on the long-term axial resistance of the piles. The emphasis is on piles installed in soils, and the response of the soil to the act of installing the pile. Although the effects of installation may be difficult to quantify, an understanding of basic principles in terms of soil mechanics is fundamental to developing engineering judgment and thereby developing and implementing an effective design, testing and quality control/assurance program to achieve reliability in the performance.

Side and base resistance

Foundation engineers typically characterize the side resistance (side shear, or side friction) per unit surface area of a pile, \( f_s \), using one of the following broadly general approaches:

For cohesionless soils:  
\[ f_s = \beta \sigma' \alpha \]  
where  
\( \sigma' \) is the effective vertical stress at a point along the pile, and  
\( \beta \) is a correlation factor related to the friction at the pile/soil interface and the ratio of horizontal to vertical stress.

For cohesive soils:  
\[ f_s = \alpha S_u \]  
where  
\( S_u \) is the undrained shear strength, and  
\( \alpha \) is a correlation factor.

For in-situ test measurements:  
\[ f_s = C(N_{sp} \text{ or } q_{sp}, \text{ or other}) \]  
where  
\( C \) is a correlation factor with the in-situ test parameter.

Generally all of the methods for estimating static axial resistance for either driven or drilled piles in soil follow some variation on the above, with the empirical correlation factors dependent on considerations such as soil type, estimated soil material properties, overconsolidation ratio, pile type or material, pile volume per unit length, installation technique, length to diameter ratio of the pile, length of pile below the point in question, depth below grade, various averaging techniques, whether the pile is thought to be plugging and other factors that may be thought to be important or relevant.

The methods for estimating base resistance (end bearing, toe capacity, etc.) per unit area at the pile base follow a similar approach with different empirical correlation parameters.

Why so many different modification factors? The following sections describe, from a soil mechanics and construction perspective, some of the important issues going on during installation of driven and drilled foundations that affect the subsequent axial resistance.

How does pile driving influence the axial resistance?

As a pile is driven, the soil in the pile location is displaced by the pile pushing past, as illustrated by Vesic (1977) in Figure 1. This action alters both the state of stress in the ground around the pile and the soil itself by remolding and/or changing the fabric and density. This figure by Vesic includes a lot of things going on in the ground that are worth our consideration in a bit more depth.

Densification of sandy soils

In granular soils such as sands, the forcible displacement of the soil coupled with vibrations typically act to densify the ground around the pile. Most "pile bucks" understand through experience the need to consider the driving sequence of piles in a large group because the last ones will likely drive harder. An example of the densification effect is described by Ruesta and Townsend (1997) from the Roosevelt Bridge in Stuart, Fla.

Ruesta and Townsend performed tests on the lateral resistance of pile groups at the Roosevelt Bridge, and included an investigation related to densification around driven piles. The Roosevelt Bridge is founded on four by four groups of 30-inch square prestressed concrete piles at 3D spacing and driven into sandy soil. The piles were installed first by jetting each pile to a depth of 25 feet, followed by driving the piles to the required driving resistance. The question of interest was related to the effect of the jetting operation on the lateral load resistance of the piles, and a load testing program was implemented including lateral tests on both single and a group of piles. As part of the research, in-situ tests were performed in the soil both within the interior of the pile group and outside the group in an area unaffected by pile installation.

The results of the in-situ tests illustrated the densification of the soil near the piles that is produced by pile driving operations, even in the soils through which jetting had been performed. The relatively loose fine sands of the upper 15 feet were densified most dramatically, with cone penetration test (CPT) tip resistance values increased by a factor of three to four and CPT friction resistance increased by six to eight. Dilatometer (DMT) modulus was increased by two to three times and the horizontal stress index \((K_0)\) increased by four to five times. Pressuremeter (PMT) modulus increased by a factor of five to eight.

These types of measurements demonstrate that any correlation of pre-construction in-situ test data with pile capacity will be subject to the changes in the actual in-situ characteristics of the soil as influenced by the pile installation.

If saturated sand is to densify, then pore water must be driven out and this action presents opportunity for transient
Since the effects of pile installation are so different between driven and drilled foundations, it is important to understand, at least qualitatively, what happens in the ground and at the pile/soil interface during pile installation.

Elevated pore pressures around the pile that could temporarily reduce the effective stress in the ground. The occurrence of significant pore pressures around piles in sand commonly occurs only in sands with sufficient fines (sils and clays) so that the sand is not freely drained. The writer has observed “sand volcanoes” in the area around pile driving operations in loose silty fine sands with shallow groundwater, but this phenomenon is relatively rare. Elevated pore pressures typically dissipate within minutes in well drained sandy soils.

Remolding and consolidation of clayey soils
In fine grained soils such as silts and clays, pore water pressures are typically generated with the soil displacement and increases in stress, and these soils have such low hydraulic conductivity that the water does not drain away quickly. The effect of pile installation on the soil and state of stress is complex and changes with time.

As the pile is driven, the soil around the pile is sheared and distorted by the displacement from the pile, with remolding of the soil fabric. After the initial displacement and radial stress increase as the toe of the pile passes a given depth, the soil adjacent to the pile is subject to cyclic shear stress at the pile/soil interface with each successive blow, developing a zone of very remolded soil immediately adjacent to the pile wall.

As excess pore pressures around the pile gradually dissipate, pore water will flow radially away from the pile and the soil adjacent to the pile consolidates and the effective stress in the soil increases; however, this change in volume near the pile wall redistributes the relative ratio of radial stresses to tangential stress around the pile. An early result of time-dependent consolidation of soil around the pile is illustrated in measurements reported by Flaate (1972) and also discussed by Karlsrud (2012).

Flaate identified the effects of consolidation in clays around piles by his measurements of shear strength and water content between piles in a group of timber piles during a test program conducted over five years after installation. A shaft was excavated to a depth of about 25 feet to obtain soil samples between the piles. Water contents of the soil at the site were typically in the range of 28 to 32%, but in the zone between...
These effects are sometimes visually observable. During a test pile program a few years ago in the Cape Fear River near Wilmington, N.C., some 10-inch diameter steel pipe piles were installed in clay soil for lateral load testing, after which the piles were extracted. When the piles were pulled (using an enormous ringer crane), the piles were coated in clay, indicating that the shear failure occurred not at the pile/soil interface but rather a fraction of an inch into the soil away from the pile surface. Likely many readers have observed similar behavior with extracted sheet piles or steel casings.

The behavior of remolded clays around a pile and the resulting side resistance is affected by the prior stress history of the soil (notably overconsolidation ratio) and can be influenced by the installation process, particularly where interruptions in driving disrupt partial setup in the soil (Saye et al, 2013).

Residual forces
Residual forces in driven piles are always present after driving due to the locked-in resistance from the pile driving operations; these forces have the effect to pre-load the pile and lock in some of the axial resistance at the pile toe with the result that the axial stiffness of the pile is increased. As a pile is impacted and compressed during driving, the soil locks-in a downward directed side resistance over the upper portion of the pile against the upward directed toe force plus some side resistance in the lower-most portion of the pile. The actual distribution depends upon the resistance at the toe and the distribution of resistance along the pile length and will likely change with time after driving. A good explanation of this effect and observations in instrumented pile load tests is provided by Fellenius (2002).

Residual forces are not easy to measure accurately and reliably, but the true distribution of side and base resistance requires accounting for residual forces. A recent load test described by Ganju et al (2020) demonstrates the results of a carefully instrumented test of a 60-foot (18m) deep 24-inch (0.6m) diameter closed end steel pipe pile that was impact driven into gravelly sand. Residual shaft resistance acted downward in the upper two-thirds of the pile against the combined upward shaft resistance and base resistance below, and these forces were around 10% of the nominal axial resistance of the pile as measured in the static load test.

Time effects
The time-dependent change (often referred to as “setup”) in axial resistance of driven piles is well documented and normally related to increasing side resistance with time. As a result, foundation engineers often wait for a period of one to
two weeks before performing a static pile load test to allow setup to occur and be reflected in the measurements. However, setup may continue for longer periods that have traditionally been considered. A series of instrumented load tests in mixed sands and clays in Florida reported by Bullock, et al (2005) show long-term increases in axial side resistance for periods up to several years, trending in a linear fashion when plotted against time on a log scale. Figure 3 shows a plot of these data with axial side resistance ($Q_s$) normalized by the axial side resistance at a time of one day after driving ($Q_{s-1d}$).

Setup is understood by most foundation engineers as related to dissipation of transient excess pore water pressures, and this effect is profoundly important in fine grained soils. However, there are other factors that contribute to pile setup, even in coarse granular soils. These can include soil aging, a well-known phenomenon that can be defined as an increase in strength, stiffness and dilatancy that is not directly related to a change in density. Aging effects have been attributed to cementation (e.g., Mitchell and Solymar, 1984) or creep effects at particle contacts (e.g., Schmertmann, 1991).

Axelsson (2000) made measurements on instrumented concrete piles in sand and concluded that pile driving can generate strong arching effects around the

Figure 3: Pile set-up measurements from five sites in Florida (from Bullock, 2005)

Figure 4: Horizontal pressure measurements on pile sidewall (from Axelsson, 2000)
Most “pile bucks” understand through experience the need to consider the driving sequence of piles in a large group because the last ones will likely drive harder.

pile that deteriorate with time, leading to a time-dependent increase in the horizontal stress acting on the pile sidewall. Figure 4 presents data from horizontal stress measurements using pressure cells embedded into the pile sidewall. The measurements shown are for depths ranging from 24 to 60 feet below grade and were made on a 9.25-inch-wide square concrete pile. He describes these effects as “stress relaxation”; however, the axial resistance is not relaxing because the effect of these changes in stress are correlated to long-term increases in measured static axial resistance in sands during periods of up to two years.

Considerable setup is known to occur in clay soils both during the period of pore pressure dissipation and reconsolidation around the pile, which can take months or longer for clays of high plasticity, and for years thereafter. The effects of aging beyond the reconsolidation phase may be attributed to chemical bonding and/or long-term increase in horizontal effective stresses as describe above. Karlsrud (2014) reported measurements of side resistance in clays increasing by as much as 55% during a period between three months and two years after driving, and a few older tests suggest that the side resistance may continue to increase for at least two decades after pile installation.

Base resistance

Piles driven to bear on hard rock can develop a base resistance that is generally limited only by the structural strength of the pile and the stresses in the pile during driving. For piles bearing on rock, the problem is therefore not so much a geotechnical problem as a structural/construction problem to install the pile without damage.

Piles driven to bear on very dense or cemented materials may also develop very high base resistance, and the presence of such a bearing layer may override considerations of side resistance, setup, etc., if strong bearing can be achieved. These types of soils are characterized by standard penetration test (SPT) values at refusal (i.e., 50b/6in or more) or refusal during cone penetration testing (CPT). The uncertainty for foundation engineers in these conditions is primarily the stratigraphy of the project site and the depth to the bearing stratum. There can be
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uncertainty regarding the potential penetration into these layers during installation of low displacement steel piles, such as H or open pipe sections that may have a relatively small bearing area. Most engineers rely on local experience and/or test pile installations to develop a rational approach to design and construction.

**Summary**

The installation of driven piles has a substantial impact on the fabric, relative density and state of stress in the soil around the pile, and the effects of these changes profoundly impact the axial resistance of the pile. Furthermore, changes in the soil, the state of stress and the resulting axial resistance of the pile occur as a function of time long after the pile is installed.

**How and why does the axial behavior of a drilled pile differ?**

The most common types of drilled foundations in soil include continuous flight auger piles (CFA), also referred to as augered-cast-in-place piles, and drilled shaft foundations, also referred to as bored piles or drilled piers. Micropiles are another common type of drilled foundation, but less commonly employed into a soil profile and so will not be directly addressed in this article. Likewise, drilled displacement piles (which are often used as a form of ground improvement and sometimes used as foundation piles) will not be included for brevity.

Drilled shaft foundations are very often installed into rock so that the structural capacity of a large reinforced concrete column can be realized. The discussion in this article will focus on the behavior of drilled foundations in soil, which may not be relevant if a drilled shaft is installed on or into rock. CFA piles generally cannot be drilled into hard rock, although they may be successfully installed into soft limestone or weakly cemented materials. The term “pile” will be used generally for both types of drilled foundations, and the term “concrete” will also be used generally even though CFA piles are typically constructed using a sand-cement grout mixture.

Both CFA and drilled shafts in soil differ fundamentally from driven piles in two main respects:

1. The pile is constructed by excavating and replacing the soil rather than by displacing it, and
2. The pile/soil interface is affected by the drilling and casting of concrete rather than by the soil remolding around a prefabricated pile element.

When a hole is excavated into the soil, the stability of the excavation must be maintained until the concrete placement is completed. The stability of a properly constructed hole is maintained in one of the following ways:

1. The soil has sufficient cohesion or cementation that it remains stable on its own, without any internal support,
2. The CFA auger flights remain filled with soil so that the sidewall does not continually collapse into the augers,
3. The drilled shaft excavation is maintained with a support fluid or casing.

Obviously, if inadequate internal support is not provided and the soil is not stable on its own, then collapse can occur resulting in subsidence around the hole and loosening of the ground that is intended to support the structure. Such
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Figure 5: Reduced horizontal stress around a hole associated with arching

The condition of the ground around even a stable hole is such that the excavation results in a reduction in lateral stress. This reduction occurs as the soil relaxes radially inward and arching forms in the tangential direction around the opening, as illustrated in Figure 5. The arching is the key to the stress relief, allowing a minimal outward radial stress to support the hole; this small supporting stress is provided by the soil-filled augers or the support fluid or the casing.

As a result of this relaxation, it is not uncommon that the soil around a drilled pile might undergo a reduction in resistance as measured in an in-situ test, as demonstrated by data shown by Bottiau (2014) on Figure 6. These CPT soundings were made at the locations of two 24-inch diameter CFA piles in medium dense sandy soil at a site in Belgium. The blue lines represent the cone tip resistance at each pile location prior to pile installation, and the green lines represent the cone tip resistance measured at a distance less than a foot away after the
pale was installed but before it was load tested. One can see from these data that any correlation of pre-construction in-situ test data with pile capacity will be subject to the changes in the actual in-situ soil characteristics as influenced by the pile installation.

One might think that casing in a drilled shaft can support high lateral stress and mitigate any relaxation; however, a high lateral stress on the casing would preclude the ability to twist it into place. Temporary casing is typically equipped with an oversized cutting shoe to reduce the friction by allowing a bit of inward soil movement so that arching around the casing can develop in the soil. One could drive the casing into place as per a driven pile, but unless it’s intended to be a permanent casing, retrieving the casing might become problematic.

As concrete fills the hole, the outward radial stress of the fluid concrete potentially recovers much of the in-situ radial stress. The resulting radial stress may be related to the concrete slump and rebar cage congestion, although the long-term

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stress at the pile/soil interface is likely to change as the ground adjusts to the conditions just as has been described and measured on driven piles. Some CFA contractors apply an overpressure during pumping to try to restore the post-construction lateral stresses in the ground, although this practice can result in overconsumption of grout and it is not clear that the effect remains long-term.

In any event, the soil around a drilled pile cycles through a process of transient stress relaxation during construction, as opposed to the transient total stress increase associated with driven pile installation.

The pile/soil interface for a drilled foundation is formed by concrete cast against the excavated soil surface, a process which undoubtedly increases the roughness compared to the pile/soil interface surface of a prefabricated driven pile. The actual roughness is difficult to quantify and is a function of the drill tooling and the soil characteristics, but clearly the surface roughness as exhibited in the exposed secant pile wall in Figure 7 can contribute to side resistance of a drilled foundation. This is not to say that all drilled foundations would appear so rough, as this feature is likely to vary widely.

When smooth wall temporary steel casing is advanced ahead of the drilling with a vibratory hammer, the frictional benefits of this roughness may be diminished, as was demonstrated by the load testing program on the Cooper River Bridge project in Charleston, S.C. as described by Camp et al (2002). However, small details can make a big difference; the drilled shafts constructed for the...
One should not anticipate that a calculation method that has been used with great reliability in the alluvial clays of New Orleans would necessarily be used with the same reliability in the Yorktown formation in Norfolk, Va. or in the coastal sand deposits of Long Island, N.Y.

Huey P. Long Bridge widening project in New Orleans were constructed using full length segmental casing with a cutting shoe equipped with teeth at the bottom. The oscillator machine works the casing back and forth as it extracts the casing during concrete placement, with the result that the cutting teeth leave a roughened surface at the interface, as evident in the photograph in Figure 8. This photograph shows the surface of one of a group of nine-foot diameter shafts that were uncovered in the cofferdam excavation during construction of the footing; the herringbone pattern in the exposed concrete surface results from the casing teeth during oscillator extraction of the casing.

Although the surface of a drilled foundation may be relatively rough, the pile/soil interface is affected by the construction operations. The soil at the interface is sheared and remolded by the passage of the tools during drilling; remolding from shearing action may be more obvious with a continuous auger and is more likely to affect the interface with clay soils. In addition, the interface of a drilled shaft can be affected by residual effects of drilling fluid. For example, published experimental results (e.g., Brown, 2002 and Brown and Muchard, 2002, Lam et al, 2010, ) have shown that mineral based (bentonite) drilling fluids can significantly affect the side resistance as compared to synthetic polymer fluids.

The base resistance of drilled foundations is also sensitive to construction operations. Compared to the residual force at the base of a driven pile, the soil at the base of a drilled pile cycles through an unloading during excavation, followed by a replacement stress from the column of fresh concrete. The contact at the base can be contaminated by drill cuttings if the base of the excavation is not adequately cleaned, or by mixing of the grout and cuttings at the toe of a CFA pile. Effective construction practices can mitigate many of the deleterious effects on base resistance, but good quality control coupled with rigorous inspection is essential for consistent quality assurance.

So how can the axial resistance of driven and drilled foundations be most reliably predicted?
If nothing else, the above discussion should remind the reader to maintain a healthy respect for the uncertainty in our ability to reliably estimate the axial capacity of deep foundations of all types. On top of the uncertainties about the variability in ground conditions, we have the uncertainties related to the effects of pile installation, which vary with construction technique and soil type. For these reasons, our estimates of axial resistance should be just that: estimates. A successful design requires some verification that the method of estimating axial resistance is reliable, usually through load testing of representative piles.

It may not be a surprise that hundreds of alternative calculation methods have been proposed for estimating the capacity of driven piles and drilled foundations of various types, ranging from theoretically based models to simple empirical correlations with in-situ tests. Why so many? Undoubtedly because of the lack of successful use of any single method across a wide spectrum of possible conditions. However, many engineers have developed predictive methods that are used with confidence for specific types of piles for specific local geologic conditions; the reliability of such methods are invariably connected to load test verification and a history of use.
So, the predictive tools or method that offers the greatest opportunity for reliability for your specific project conditions requires that the method must be correlated to:

a) The specific ground conditions at the site, based upon an understanding of the unique geologic characteristics and the methods used to quantify specific soil properties,

b) The specific pile type and installation methods, including specific details that can influence the results, and

c) Representative load test results that provide a reliable measurement of axial resistance of the pile.

For example, one should not anticipate that a calculation method that has been used with great reliability in the alluvial clays of New Orleans would necessarily be used with the same reliability in the Yorktown formation in Norfolk, Va. or in the coastal sand deposits of Long Island, N.Y. The geology is different, and the nature and fabric of the soils are different. Likewise, a method that has been demonstrated through load testing to work quite well in a specific locale with prestressed concrete piles cannot be expected to have similar reliability with steel H or pipe piles in the same conditions until a base of experience and correlation with load test results is established. For example, CPT testing with pore pressure measurement (CPTu) can be a great tool for development of correlations of pile capacity, but if all of the historical pile test information of specific relevance to your project has only SPT data then you cannot expect great reliability with the CPTu until you evaluate load tests in similar conditions with CPTu data. One might consider performing multiple types of tests with the goal of ultimately improving the practice by using CPTu.

Fortunately, advances in load testing afford foundation engineers the opportunity to make reliable measurements of axial resistance on full scale piles and on a project-specific basis. Conventional static load testing remains the gold standard for measurement, although even static load tests can be subject to imperfections (e.g., Hussein et al, 2012). Dynamic load testing has become a routine part of driven pile construction and provides
Environmental or public relations aspects of pile installation such as noise and vibration, real or perceived, often influence some public agencies to avoid pile driving.

a rational means of verification that the axial resistance of production piles is achieved, subject to limitations (set-up time, full mobilization of resistance, pipe pile plug behavior, etc.). Static, dynamic and rapid load testing can be performed on CFA piles in the same way, although routine testing of production piles is not a routine part of verification as for driven piles. Bi-directional load cell testing of drilled foundations enables loading of large diameter to substantial loads of a magnitude that may be impractical with conventional testing.

The point of this discussion is that the reliable prediction of any deep foundation element requires performance verification through field measurements, and fortunately for foundation engineers, such measurements are obtainable with current technology. The key to success is that field load testing be performed with an understanding of the specifics of both the unique ground characteristics for the project and for the specific installation details pertaining to the piles.

So how does the axial resistance of driven and drilled foundations compare?
The multitude of factors influencing performance preclude a definitive broad general answer to this question. However, an understanding of the principles reviewed in the preceding pages may provide some ideas, when coupled with a lot of experience in testing different types of piles. The author’s general thoughts are as follows, which are necessarily very general, subjective and reflective of personal experience. And, of course, there are often factors other than load-carrying efficiency that affect the selection of the type of deep foundation.

The worse the ground conditions, the more conditions generally favor driven piles over drilled foundations. Loose or weak soils present stability problems for drilled foundations and these represent potential construction risks as well as inefficiency.

More granular soil deposits tend to favor driven piles because of the beneficial effects of the ground improvement associated with displacement piles and the potential relaxation associated with drilled foundations.

Stronger cohesive or cemented soils favor drilled foundations; the favorable conditions for borehole stability combined with the benefits of sidewall roughness can promote excellent side resistance.

Other major factors affecting foundation type selection include:

- Lateral loads and flexural strength demands; large diameter drilled shafts often benefit from demands associated with high seismic loading or liquefaction-induced lateral spreading, although large diameter steel pipe can also be efficient in these circumstances.
- Marine conditions: over-water work favors the simplicity of driving piles unless expensive underwater cofferdam work is required.
- Congested sites and nearby structures tend to favor large diameter drilled shafts if the footprint associated with the foundation can be reduced to a single shaft. However, a group of smaller piles provides redundancy.
- Many piles to be installed close proximity for a footing can favor driven piles if staging of cast-in-place piles complicates construction sequencing.
- Environmental or public relations aspects of pile installation such as...
noise and vibration, real or perceived, often influence some public agencies to avoid pile driving.

In the author’s experience with design-build project delivery, most questions about which type of pile to use start with the question, “How can we build things most easily and meet the schedule?” followed closely by, “How much will it cost?” and, “What are the risks?”

There are risks associated with uncertainty about pile capacity, and these may vary with confidence and experience associated with each pile type. Risks may also include schedule and other risks associated with hiring specialty subcontractors, which can be a consideration when the general contractor can self-perform some types of foundations under consideration but not all. Unless there are other considerations such as owner-specified limitations (e.g., see the last bullet above), all viable foundation types will be seriously evaluated.

**Conclusions**

The principal lessons that the readers should take from this discussion are summarized as follows:

- All types of deep foundations influence the ground as a part of the process of installation,
- All the available methods of estimating pile capacity include empirical correlation factors that are subject to the many specific conditions and uncertainties at the specific locations of load test from which the empirical correlations were developed,
- The post-construction conditions of soil characteristics, in-situ stresses and influence on the pile to soil bond strength is quite complicated and not captured by any simple equation,
- Given all of the above unknowns and uncertainties, reliability in foundation design is critically dependent on a robust testing plan that incorporates the important aspects of construction for the specific ground conditions of the project.

The author hopes that the readers find this discussion of the many hard to calculate issues affecting pile behavior to be interesting and informative rather than discouraging. As my father once told me as I was about to leave home for college almost 50 years ago, “Son, the more you learn, the more you find out how much you don’t know.”

**References**

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