Emergence of New Properties at the Large Scale on Elastic Surfaces due to Small-Scale Adhesion and Waviness

1 Introduction

1.1 Research objective (Ro):

We seek to understand if and how friction-type behavior can appear ("emerge") at the large scale on surfaces that are intrinsically frictionless at the small scale. This will be done by quantitatively understanding the origin and operation of any new dissipative mechanisms that are created by the the surface's small-scale adhesion and architecture.

The adhesion (or "stickiness") of a contact interface is quantified through the adhesion energy, w [1, p. 30]. The parameter w is defined to be an intrinsic property of the contacting pair of surfaces. Roughly speaking, w is a measure of the energy consumed when mechanically separating two surfaces that are in contact. However, recently the PI [2, 3] showed that in addition to w, small-scale surface architecture can have a dramatic effect on the net energy that is consumed during the separation process. This is because the small-scale architecture, coupled with w, can give rise to new energy dissipating contact instabilities at the small scale. Due to this phenomenon, the effective adhesive energy, w_{eff}, which is the adhesive energy that is actually measured at the large scale, can be quite different from w. The w_{eff} is not an intrinsic material property and is a function of both w and the small-scale surface architecture. These findings open up a fascinating array of new questions and research directions, such as: (i) Will it be possible to produce a surface with any prescribed w_{eff} through designing its small-scale surface architecture? If so, what is the maximum w_{eff} that can be achieved? (ii) Can w_{eff} depend on bulk elastic properties, such as Young's modulus, or bulk deformation of the solids? If so, then can w_{eff} be reversibly modulated by cyclically straining the solid? (iii) Due to adhesion, the bodies can remain in contact even when the applied normal force is tensile. As per Coulomb's law, applying a normal compressive force increases the tangential ("frictional") force. However, how does the tangential force vary when the applied normal force is tensile, rather than compressive? Will Coulomb's law still apply? If it does, then the coefficient of friction will be negative. Finally, will it be possible to design surface architectures through which one can modulate the normal tensile force by applying a tangential force? This will be tantamount to creating a Coulomb's law that acts in reverse. One can similarly envision the vast variety of amazing technologies that can result by answering such questions. For example, answering (i)–(ii) will lead to the development of novel pick-and-place technologies that can be used for handing small, delicate objects, such as electronic and MEMS components. Answering (iii) will lead to the development of novel surfaces in which friction can be used to control adhesion, and vice versa. Such materials will increase the agility and robustness of the next generation of climbing robots. Important questions such as (i)–(iii) can only be answered through the pursuit of the objective Ro.

1.2 Research strategy:

We split the primary objective into two parts: ($Ro.1$) Understand the nonlinear contact phenomena (e.g. instabilities) that are precipitated at the small scale by the surfaces' small-scale architecture and w, and ($Ro.2$) Understand how those small-scale phenomena give rise to effective frictional behavior at the large scale. We will achieve $Ro.1$–2 by studying a model family of adhesive, elastic contact problems in transverse loading. We idealize the surfaces' small-scale architecture using wavy profiles. The wavy profiles can be models for the often periodic structural features seen in biological surfaces or recently being engineered on elastomeric materials using soft lithography and surface wrinkling techniques. We do not attempt to study fractal or stochastic topography, which would be a better model for natural surfaces. This is done in order to make the problem theoretically tractable, since the proposed approach is new. Eventually, after the successful completion of the current project, we believe that we will be in a better position to analyze the micro-mechanics of stochastic and fractal surfaces.

We describe these contact problems in sec. 3 and will study these problems using a synergistic combination of theoretical analysis, computer modeling, and experiments, which are described in 3.1.

1.3 Novelty of the research objective:

The concept of new properties emerging at the large scale as a consequence of material architecture at the small scale has been investigated thoroughly over the last several decades by the composites and mathematical homogenization communities [9–14]. However, those earlier investigations focused exclusively on bulk material properties, such as elastic stiffness and thermal conductivity. We, however, will be focusing on surface properties. Apart from the PI's most recent work [2, 3, 15] and the work by Mohammadi et al. [16], a negligible fraction of the earlier works focus on problems regarding how small-scale architecture can give rise to new large-scale properties on surfaces.

The proposed research focuses on the mechanics of contact during transverse loading between elastic solids whose surfaces are intrinsically adhesive but frictionless. By intrinsically adhesive and frictionless we mean that the contacting surfaces are capable of supporting tensile normal tractions (adhesive) but not shear tractions (frictionless). We also only consider elastic behavior for the contacting solids. A huge amount of work has been done on understanding the mechanics of contact. The literature on the mechanics of elastic, non-adhesive, frictionless contact dates back 1881 [17], while elastic contact between adhesive, frictionless surfaces has been studied since the 1970s [1, 18–20]. A huge number of different contact geometries and contact-laws (relating to both adhesion and friction) have been studied using a variety of analytical [21–24] and computational techniques [25–30] including finite elements (cohesive zones [31]), atomistic simulations (molecular dynamics [32]), and hybrid "multi-scale" techniques (quasi-continuum techniques [33]). Considering the sheer magnitude of the journal articles and monographs published on the subject, it is reasonable to wonder whether there can be any new significant discoveries in this direction at all. As mentioned earlier, the proposed research is focused on the case of elastic contact between surfaces that are intrinsically adhesive and frictionless. The earlier studies on adhesive, frictionless contact have primarily focused on the case of normal loading, i.e., where the solids are displaced only in the direction normal to the contacting surfaces. Transverse loading has also been studied thoroughly, but only in the case of non-adhesive contact [34–36]. The proposed research focuses on the completely fresh case of transverse loading of adhesive, frictionless surfaces.

The proposed case may superficially appear to be not substantially different from the earlier studied cases, however, this is not true. A preliminary analysis of the proposed case (see sec. 3.2.1) shows that even though the surfaces are intrinsically frictionless, dissipative effects can appear solely due to the surfaces' adhesion and architecture. This behavior, which is unique to the proposed case, can lead to the appearance of frictional behavior at the large scale. Dissipative effects appear in contact problems in which the surfaces possess some intrinsic friction [37, 38], however the surfaces in the proposed research are intrinsically frictionless. Thus, the exciting and novel aspect of the proposed case is that dissipative effects (and hence effective friction-type behavior at the large scale) can appear despite the surfaces being intrinsically frictionless (i.e., frictionless at the small scale).

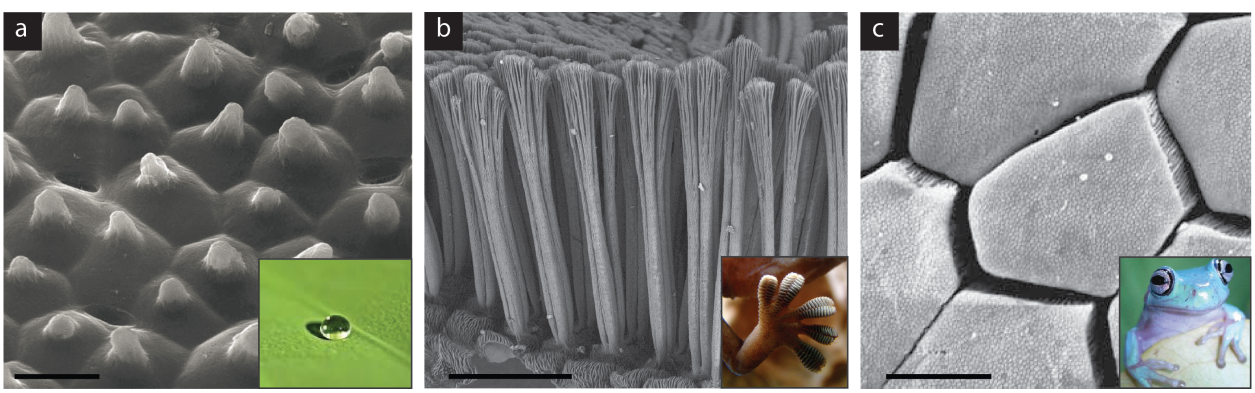

Figure 1: Examples of biomaterial surfaces with known structure-property connections. (a) shows the SEM micrograph of a lotus leaf surface, which consists of sub-$\mu\mathrm{m}$-sized asperities providing roughness at the microscale [4] (Inset: a water droplet floating on a lotus leaf [5]). (b) shows the sub-$\mu\mathrm{m}$ bristle-like structures [6] on a gecko's foot [7]. (c) shows the microstructure of epidermis of a tree frog toe with hexagonal epithelial cells (Inset: a White's tree frog (*Litoria caerulea*)) [8]. The scale bars shown in (a–c) measure $10\,\mu\mathrm{m}$, $5\,\mu\mathrm{m}$, and $50\,\mu\mathrm{m}$, respectively.

1.4 Intellectual Merit: longer term vision and significance

The proposed research will take us towards a fairly new unexplored territory of applied mechanics that can be termed "micro-mechanics/homogenization of surfaces and interfaces". The proposed research will lead to the discovery of a fascinating array of completely new results, describing how friction, adhesion and surface architecture are coupled at the small scale, and how new surface properties can emerge at the large scale as the smeared out effect of new mechanisms that are created at the small scale by the adhesion and architecture. Thus, the proposed research will yield fundamental, new results that are intellectually rich and of great scientific value.

The proposed research should be viewed in the context of the current approaches used in the modeling of surface phenomena. Friction and adhesive phenomena have traditionally been investigated through experimental means, where simple phenomenological models were fitted to the data. In the current approaches friction, wetting, and adhesion hysteresis are considered intrinsic properties of the surfaces and are modeled using phenomenological models [39]. Although the phenomenological models might suffice for some rough engineering needs, they are far from satisfactory as scientific theories. A mathematically rigorous, theoretical understanding of the origin of surface mechanical phenomena is currently lacking. There is very limited understanding of the small-scale mechanisms that underlie surface phenomena, and how surface phenomena are connected to small-scale parameters (intrinsic adhesion, roughness, etc.) Understanding structure-property connections of surfaces would provide a deeper understanding of surface mechanical behavior. It would reveal the mechanisms underlying the surface behavior and explain how the behavior is related to small-scale parameters. We believe that our work will eventually lead to the development of rigorous micro-mechanics theories of friction and adhesion. Such theories will explain the origin of various recently-reported adhesion-friction phenomenon, such as frictional-adhesion [40] and switchable adhesion [41].

In the long term, the results of the proposed project will galvanize scientific and technological breakthroughs in many related disciplines. For example, they will ease current bottlenecks in the fields of soft-robotics and micro-electromechanical systems (MEMS). Tactile sensors that are capable of reproducing the human sense of touch are widely recognized as critical for improving the ability of robots to grasp delicate objects without causing them undue damage [42]. However, creating such sensors requires a thorough understanding of how the frictional effects that produce tactile sensations are related to small-scale surface structure (texture). Unwanted adhesion between micro-machined structures (stiction (sticking+friction) failure) continues to cause reliability concerns in MEMS devices [43, 44]. Our results will enable the maturation of technologies, such as pick-and-place technology [45, 46] and climbing robots [47]. Our results will be a timely and ideal counterpart to the upcoming fields of 3D printing and digital manufacturing. In alliance with these technologies, they will allow engineers to create designer surfaces, i.e., surfaces that possess a prescribed set of surface mechanical properties. They will inform us of the correct sizes, shapes and arrangements of surface features to be used in order to produce the desired effects in a highly precise manner. We envision that such "structural surface engineering" will be capable of producing completely novel and exotic surface effects. For example, consider again our earlier question of whether it is possible to produce a Coulomb's law that acts in reverse.

2 Background Information

2.1 Motivation

Small-scale surface features give rise to some very remarkable and fascinating new properties at the large scale. This fact is especially evident in biological systems (Fig. 1). For example, the bumpy protrusions on the surface of the lotus leaf have been shown to endow the leaf with the property of super-hydrophobicity (non-wettability) at the large scale [48]. This non-wetting property is the root of the lotus leaf's acclaimed *self-cleaning* ability [49]. The periodic, small-scale, wavy undulations seen on the skin of some sharks are thought to reduce the sharks' skin friction drag [50]. Most pertinent to the proposed research, however, are the examples of the gecko and the tree frog. The gecko lizard can scale walls without the use of any claws or liquid secretions [51, 52]. Its toes are covered with thousands of small-scale hair-like surface features whose dimensions and shape enable the gecko to exploit van der Waals forces to strongly stick to and easily unstick from a variety of surfaces (Fig. 1 b). The toe of the tree fog is split into hexagonal patches that have deep grooves between them [8] (Fig. 1 c). It is argued that the groves allow water to seep away from the contact area, thus minimizing hydroplaning and allowing the frog to better grip wet surfaces [53].

The above examples highlight that small-scale surface features can have a profound effect on the large-scale physical behavior of surfaces. This intriguing link between small-scale surface structures and large-scale surface properties is not limited to biological surfaces. It was in fact first demonstrated on engineering surfaces that friction and adhesion are strongly affected by surface roughness [54]. However, the surface structure-property connections are much more clear in biological surfaces. Irrespective of whether we are studying biological or engineering surfaces, it is important to note that the new properties at the large scale are primarily a consequence of the surfaces' small-scale architecture (dimensions, shape, etc.), and not their chemistry or material composition (for justification see e.g. [49] and the references therein). In a crude sense, the principle is analogous to how new colors appear on a computer screen at the large scale primarily as a consequence of the arrangement of the red, blue, and green pixels at the small scale.

2.2 Hypothesis underlying the proposed research

To us the biological surfaces mentioned above appear as remarkable case studies in which *new surface properties/physics emerge at the large scale as the smeared out effect of multitudes of complex interactions that take place at the small scale due to the properties and the architecture at that scale*. In the mechanics of materials community it is common knowledge that material properties can be affected by small-scale structural features and properties. For example, in metals the bulk property of yield stress is known to be strongly affected by the grain sizes (see e.g. the Hall-Petch equation [55, p. 274]). In composites, bulk properties such as the effective stiffness tensor [56–58] and fracture toughness, are known to be affected by the dimensions, shape, and arrangement of the inclusions [59–61]. The study of how small-scale structure affects large-scale properties usually falls under the umbrella of structure-property investigations. Thus far, structure-property investigations have predominantly focused on bulk properties. Our long term goal, however, is to conduct structure-property investigations on the emergence of surface and interface properties. This planned line of investigation, as we have already mentioned, is new and we believe that it holds great promise for leading to the discovery of many new, important mechanics principles of deep scientific value; we have elaborated on this fact in sec. 1.4. Thus, the proposed project will inaugurate an important line of investigation.

We will begin the new line of investigation by focusing on understanding the emergence of large-scale frictional behavior due to small-scale adhesion and surface architecture. More specifically, through the proposed project we will investigate the following hypothesis.

Hypothesis (Ho): *A significant fraction of friction on elastomeric material surfaces results from the multitudes of energy dissipating contact instabilities taking place at the small scale (sub-*mm *scale) due to adhesion and surface roughness.*

Our hypothesis is supported by the growing body of evidence that at the nano-scale, adhesion is intimately related to sliding friction [62–64], rolling friction [54, 65], wear and other very interesting tribological phenomena [62, 66]. More directly, the hypothesis is motivated by some recent, interesting results obtained by the PI.

2.3 Previous and current work that motivates our hypothesis

In experiments that involve contact with adhesion between two surfaces, as found in atomic force microscopy (AFM) or nano-indentation, two distinct contact force (P) versus indentation-depth (h) curves are often found depending on whether the indenter moves towards or away from the sample (see Fig. 2 a). Specifically, the surfaces appear more adhesive during the unloading stage and less adhesive during the loading stage. This phenomenon is termed adhesion hysteresis and has been observed in a wide variety of experiments involving compliant (e.g. elastomeric) surfaces [64, 65, 67–69]. The origin of this hysteresis was not well understood and is often attributed to moisture, plasticity, viscoelasticity, or material-specific mechanisms such as polymer interdigitation [64].

The most important adhesive, elastic contact mechanics theories were developed by Johnson et al. [18], Derjaguin et al. [19] and Maugis [20]. These theories are commonly referred to as JKR, DMT, and Maugis-Dugdale, respectively. These theories do display hysteresis, however the hysteresis captured by them is qualitatively different from the one observed in experiments. In experiments the hysteretic energy loss is observed to depend on the maximum indentation depth (marked $|h_{\min}|$ in Fig. 2 a) in a load-unload cycle. However, the classical contact theories predict the energy loss to be independent of $|h_{\min}|$.

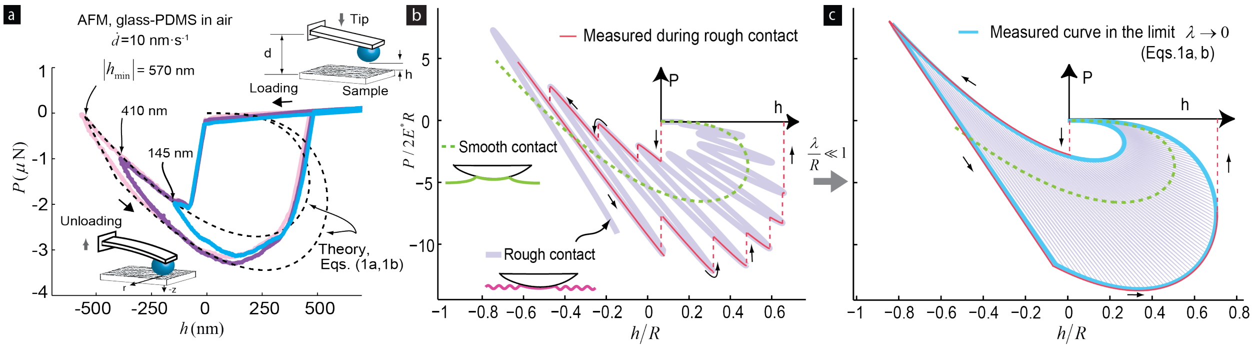

Figure 2: (a) AFM contact force P as a function of indentation-depth h (shown marked in (a)) during contact of glass and PDMS in air at an indenting rate of $\dot{d} = 10\mathrm{nm/s}$, (b) the P–h curves predicted by a smooth-surface contact model and by wavy-surface ("rough") contact model, and (c) the measured P–h curve described by eqs. (1a)–(1b) that are derived by studying the asymptotic behavior of wavy-surface contact model in the limit of $\lambda \to 0$ (figure adapted from [2])

The PI's experiments [2] and continuum mechanics based theoretical work [3] showed that hysteresis can exist without moisture, plasticity, or viscoelasticity and that its magnitude depends on surface roughness. The continuum mechanics models involved approximating the surface roughness with axisymmetric waviness of wavelength λ. As seen in Fig. 2 b, the surface waviness can create many metastable states for the contact interface at each value of the loading parameter h. The hysteresis results from the fact that the system visits the state with the smallest contact size during the loading stage and the state with the largest contact size during the unloading stage (Fig. 2 b). The energy loss is the result of a series of surface instabilities (marked with dashed magenta lines in Fig. 2 b), in which the contact area grows or recedes by a finite amount. As $|h_{\min}|$ increases, so do the number of instabilities and hence the energy loss.

Studying the asymptotic behavior of the continuum theory in the limit $\lambda \to 0$ (Fig. 2 b $\to$ c), it was found that the (h, P) points measured in an experiment would satisfy the equations

$$P(a) = \frac{4E^*}{3R}a^3 - \sqrt{8\pi w E^*}a^{3/2} \pm 2\pi E^* A\lambda^{1/2}a^{3/2}, \tag{1a}$$

$$h(a) = \frac{1}{R}a^2 - \sqrt{\frac{2\pi w}{E^*}}a^{1/2} \pm \pi A\lambda^{1/2}a^{1/2}, \tag{1b}$$

where a is the contact radius, E^* the plane strain Young's modulus, $A\lambda$ is the amplitude of the surface waviness, and R is the radius of the spherical indenter. The $+$ and $-$ signs correspond to the loading and unloading stages of the experiment, respectively. The eqs. (1a)–(1b) reveal that even though the intrinsic work of adhesion, w, remains constant, the experiments measure a higher effective work of adhesion of $w_{\text{eff}}^{1/2} = w^{1/2} + A(\pi E^*\lambda/2)^{1/2}$ during the loading state and a lower value of $w_{\text{eff}}^{1/2} = w^{1/2} - A(\pi E^*\lambda/2)^{1/2}$ during the unloading state. In summary, surface architecture at the small scale can produce a hysteretic energy loss at the large scale.

Based on these results it is natural to wonder what role small-scale adhesion and surface architecture play in other large-scale dissipative phenomena, such as friction. This thought was the motivation behind the formulation of Ho.

3 Proposed research

Problem statement: In order to make the research project concrete, well-defined and manageable, we will focus our research on analyzing the following model family of contact problems. We consider 2D contact between two solids, such as those sketched in Fig. 3. The surfaces of the contacting solids are intrinsically frictionless, by which we mean that at each contact point the traction vector is perpendicular to the local surface tangent plane (see inset in Fig. 3 b). When a traction vector points into the surface it is termed compressive and when it points away from the surface it is termed tensile or adhesive (see inset in Fig. 3 b). Though frictionless, the surfaces are assumed to be adhesive, i.e., they can support both compressive and tensile tractions. We will model adhesive interactions by either using the JKR theory or by assuming that the material particles of the contacting solids interact via a Lennard-Jones type potential. We model the surface architecture through wavy profiles, which are profiles that can be approximated using Fourier series. Such profiles will be periodic and continuous, but they do not have to be differentiable. We denote the wavelength of the undulations as λ. The shape of the undulations will be encapsulated by a finite set of dimensionless parameters. For example, if the undulations were a single sine curve of amplitude $A\lambda$, then A would be the single dimensionless shape parameter. The deformation of the contacting solids is modeled using continuum mechanics theories. We assume Hookean or neo-Hookean perfectly elastic behavior for the contacting solids. The loading program involves bringing the solids into normal ($\hat{e}_2$ direction in Fig. 3) contact and then moving them in the transverse direction ($\hat{e}_1$) relative to each other in a quasi-static manner. We ignore all inertial effects. We analyze the model contact problems using both theory and computations. The aim of the analysis is to gain insight into some critical questions relating to the connection between large-scale friction, and small-scale adhesion and waviness. We elaborate on these questions using the following thought experiment.

Consider the contact between the linear elastic solid of Young's modulus E and Poisson's ratio ν and the rigid solid shown in Fig. 3. The solids are brought into contact and pressed together by applying a force of magnitude P_N in the $-\hat{e}_2$ direction . Following that, the solids are slid over each other by applying a force of magnitude P_T in the transverse direction. When the solids' surfaces are flat, as shown in Fig. 3 a, then obviously no force is needed to slide the solids over one another, i.e., $P_T = 0$. Imagine now that while keeping the surfaces' intrinsically frictionless and adhesive nature intact, the surfaces are molded into a wavy shape (see Fig. 3 a$\rightsquigarrow$ b). In this case P_T would no longer be zero. This is to be expected since even though the contact tractions are still parallel to the surface normals they will have a component in the transverse direction due to the surfaces' wavy topography.

It is reasonable to expect that P_T would also be periodic with a wavelength closely related to λ. The interesting question to ask now is what happens to the mean value of P_T as λ becomes small in comparison to a, the nominal size of the contact region (see Fig. 3 b). That is, **Q1.** as $\lambda/a \to 0$ would $\langle P_T \rangle \to 0$, or would it asymptote to a finite value? Here $\langle P_T \rangle$ denotes the spatial average of P_T over the nominal contact region. **Q2.** If $\langle P_T \rangle$ asymptotes to a finite value, how would that value depend on P_N? Specifically, when the solids are pressed together ($P_N > 0$) would the relation between $\langle P_T \rangle$ and P_N as $\lambda/a \to 0$ be similar to Coulomb's friction law, in a manner such as $\langle P_T \rangle = \mu_{\text{eff}} P_N$, where μ_{eff} is a dimensionless constant? Or would $\langle P_T \rangle$ be related to P_N in a completely new, unexpected manner? **Q3.** If a Coulomb friction law behavior were to emerge, then how would the constant μ_{eff} (the friction coefficient) depend on E, ν and A? Let us also consider the equally interesting case where the solids are pulled apart ($P_N < 0$). **Q4.** Recall that the surfaces are intrinsically adhesive, therefore a critical amount of pulling force must be applied in order to break the contact. Before the contact is broken, how is $\langle P_T \rangle$ related to P_N?

The aim of the project is to answer questions Q1–4 in our model family of contact problems. We will pursue this aim through a synergistic combination of theoretical analysis, computational modeling, and experimental measurements. These tasks will mutually guide and reinforce each other.

3.1 Research plan: aims and tasks

The overarching aim of the project is to ascertain the validity of our hypothesis Ho. We will pursue this aim by answering the questions Q1–4 in the context of our model family of contact problems. The answers to Q1–4 will be determined by pursuing the sub-aims A1–4, and by carrying out their associated tasks.

Aim 1 (A1): Through theoretical analysis determine the forces $\langle P_T \rangle$ and P_N as functions of each other, and the small-scale parameters w and the dimensionless constants that characterize the shape of the surface undulations (e.g. A).

Task A1.T1 *Solve the transverse, adhesive, elastic contact problem between simple solids (TAC-1 problem).* Study contact between simple geometries such as spheres, cylinders, and truncated cones. Determine P_T, P_N as a function of problem parameters. Identify any energy dissipating contact instabilities. Identify any important dimensionless parameters that govern the energy loss from the instabilities.

Task A1.T2 *Solve the transverse, adhesive, elastic contact between two half-spaces with wavy surfaces (TAC-2 problem).* In order to solve TAC-2 it is first necessary to solve the problem of normal, adhesive, elastic contact between half-spaces having arbitrary surface waviness (NAC-2

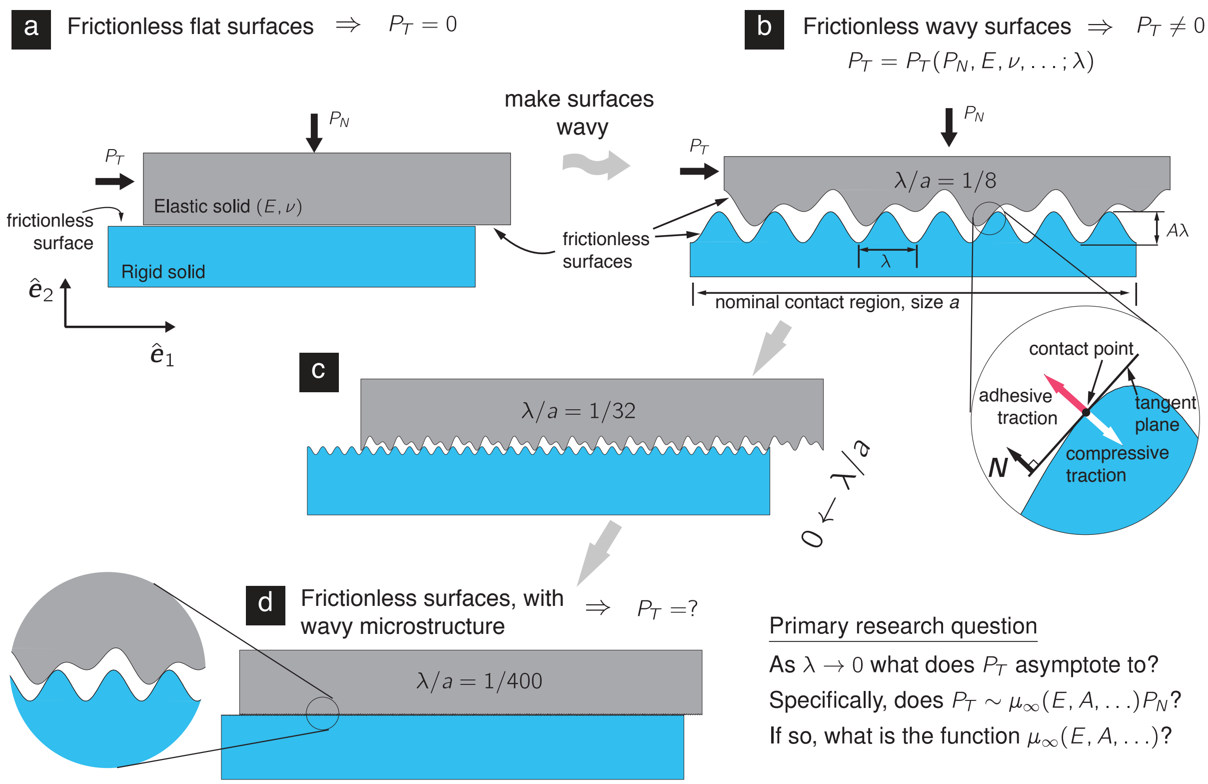

Figure 3: Research objective. A thought experiment on how frictional effects can originate purely from from the surfaces' topographies and adhesion.

problem). Use the insight from TAC-1 problem and the solution of the NAC-2 problem to solve TAC-2 (see sec. 3.2.1 for details). From the solution of the TAC-2 problem determine the eq. (2) that relates P_T, P_N to the dimensionless shape parameters of the undulations and the intrinsic bulk and surface properties of the solids.

The problems in Tasks A1.T1–2 will be solved using analytical and semi-analytical techniques (e.g. those used in [70]).

Task A1.T3: *Asymptotic analysis of eq.* (2) Use asymptotic analysis guided by numerical calculations to determine how eq. (2) evolves as the length scale of the wavy undulations, λ, is shrunk to be small compared to the macroscopic dimensions of the solids. Specifically, study the limit $\lambda/a \to 0$ of eq. (2) and derive the asymptotic relation (3). The mathematical techniques that will be used in the asymptotic analysis will be similar to the ones used in [3].

Aim 2 (A2) Develop and use computer simulations to guide A1.T2 and A1.T3.

Task A2.T1 Develop the new body-force field based contact simulation technique (see sec. 3.3 for details). Use the solutions derived through A1.T1 to benchmark the computational technique. The developed body-force field technique should be able to reproduce the results (esp. contact instabilities) of the problems studied in A1.T1.

Task A2.T2 Verify the theoretical result eq. (2) using the body-force field technique.

Task A2.T3 Guide the derivation of the asymptotic relations (3) from eq. (2).

Task A2.T4 Develop a generalized version of the body-force field simulation technique that is capable of handling arbitrary geometries for both solids. This would allow us to also use the data from other experiments, which use contact configurations that are different from ours, to further check Ho.

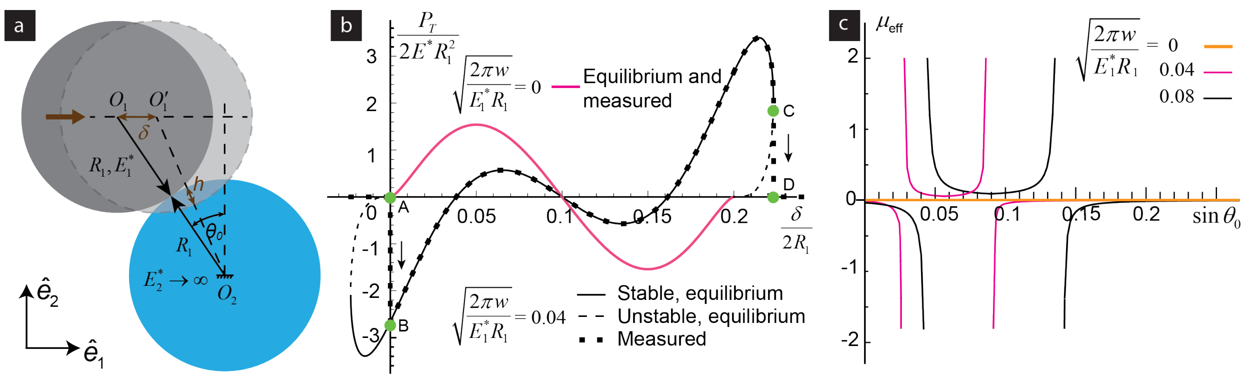

Figure 4: Preliminary results of adhesive contact of two spheres under transverse motion (see sec. 3.2.1 for details)

Aim 3 (A3) Experimentally ascertain the validity of the theoretical results derived via A1.T2–3.

Task A3.T1 Construct a mechanical testing stage (MTS) for adhesive contact mechanics studies. The MTS is designed to most closely resemble the conditions of the problems studied through A1.T1–2. That is, the contact bodies' geometries, loading rates, loading program, surface waviness, and the manner in which λ is shrunk will all be closely reproduced in the experiments.

Task A3.T2 Measure $\langle P_T \rangle$, $\langle P_N \rangle$ on a variety of elastomeric materials using different punch shapes (see Fig. 6 c) to verify the theoretical prediction eqs. (3). The designed experiments are stiffness controlled, therefore P_N cannot be held constant during the experiment. The experiment will measure the average value $\langle P_N \rangle$.

Aim 4 (A4) Project evaluation and conclusion.

Task A4.T1 Consolidate the results gathered through pursuing A1–3 and answer questions Q1–4. Determine whether Ho is true or false.

Task A4.T2 Prepare results for publication.

Research products: (i) *Primary products:* New scientific knowledge (eq. (2) and eqs. (3)) of how large-scale frictional effects are connected to small-scale adhesion and surface architecture parameters. (ii) *Secondary products:* (ii.1) Novel computational technique that is capable of simulating contact between elastic solids for arbitrary loading. (ii.2) Developments in applied mechanics and mathematics techniques for performing "homogenization of surface properties", i.e., connecting large-scale and small-scale properties. (ii.3) Adhesion and friction force measurements and visualization of any contact instabilities on highly idealized wavy surfaces. (ii.4) Introduction of 3D printing into contact mechanics research.

3.2 Aims and tasks: technical details and preliminary results

3.2.1 A1, Theoretical modeling and analysis

A1.T1: Solve the transverse, adhesive, elastic contact between simple solids (TAC-1 problem) We will solve the TAC-1 problems in order derive preliminary understanding of the important variables, their scaling and the relevant mechanisms in the problem. We studied the TAC-1 problem relating to contact of two spheres as a rough, first attempt. Figure 4 contains the preliminary results, which show how dissipative effects can arise as a consequence of adhesion and surface geometry. In the 2-sphere problem, the top sphere is isotropic, linear elastic with a plane strain Young's modulus of E_1^*, and the bottom sphere is rigid. Both spheres have a radius R_1 and can be thought of as a pair of interacting asperities on the surfaces of the elastic and rigid solids shown in Fig. 3. The rigid sphere is held fixed, while the elastic sphere is moved a distance δ in the transverse condition ($\hat{e}_1$ direction in Fig. 4 a). In the normal direction ($\hat{e}_2$ direction), the centers of the spheres are kept at a fixed separation of $2R_1 \cos\theta_0$, where θ_0 is shown marked in Fig. 4 a. The loading is displacement controlled. Adhesion between the solids is modeled using the JKR theory [18]. Even though the deformable body involved is linear elastic, the problem as a whole is nonlinear due to the presence of the adhesive forces and the fact that the contact area grows nonlinearly with δ. For this reason, at any given δ there can exist one, two, or even three equilibrium states. The stabilities of the different equilibrium states are in general different, especially when the equilibrium states correspond to the same δ. The forces and the contact region sizes corresponding to the different equilibrium states are similarly different. The forces P_T corresponding to all of the equilibrium states at each δ are shown in Fig. 4 b. The (δ, P_T) points that correspond to stable states are connected by solid lines, while those corresponding to unstable states are connected by dashed lines. The set of (δ, P_T) points that the system passes through in a virtual contact experiment are shown marked using squares in Fig. 4 b. The system transitions in a non-equilibrium (unstable) manner from the state $A \to B$, and then again from $C \to D$, which are contact instabilities that dissipate the system's energy. These instabilities are similar to the buckling type instabilities (bifurcations) that are well known in the field of structural mechanics. They are also related to the *pull-in*, *pull-off* instabilities observed in the normal, adhesive contact problems modeled using the JKR theory. We computed the cumulative energy dissipated per unit nominal contact area to be $\mathcal{H} = cw^{\frac{5}{3}} \left(E_1^* R_1\right)^{-\frac{2}{3}}$ ($c \approx 0.82$). Note that when there is no adhesion $\mathcal{H} = 0$. More interestingly, $\mathcal{H}$ also vanishes when $R_1 \to \infty$, i.e., as the surface becomes flatter. Thus, both adhesion ($w \neq 0$) and a non-flat geometry (finite R_1) are essential for dissipative effects to appear.

Motivated by Coulomb's law, we define an effective friction co-efficient μ_{eff} as equal to $\langle P_T \rangle / \langle P_N \rangle$, where the average $\langle \cdot \rangle$ is defined over the δ values between which the spheres interact. Numerically computed values for μ_{eff} are shown in Fig. 4 c. The parameter μ_{eff} is observed to increase with w and decrease with E_1^* and R_1. This supports our hypothesis that a rigorous micromechanics theory of friction might depend on both surface (intrinsic adhesion, surface architecture) and bulk mechanical properties. Fig. 4 c shows that μ_{eff} can sometimes be negative. We will check whether these anomalous, but highly interesting, results persist in our more sophisticated contact models that we will study using tasks A1.T2 and A2.T1.

Despite its simplicity, the 2-sphere problem is able to give us a glimpse into the rich nonlinear mechanics that can arise in the proposed family of contact problems. These preliminary results support our hypothesis (Ho) and justify further investigation of the new type of contact problems that we are proposing.

A1.T2, Solve the transverse, adhesive, elastic contact between two half-spaces with wavy surfaces (TAC-2): The most important feature that is missing in the TAC-1 family of problems is the interaction between the different contact patches (asperities) that takes place via the internal stress fields. In order to determine these effects we will solve the transverse adhesive contact problem between two half-spaces. Such problems have been analyzed in [71–74]. We will model adhesion again using the JKR theory. Despite the acknowledgement that the TAC-2 family of problems are very important for understanding the microscopic origins of friction (e.g. see introduction section in [74]), there have been very limited analytical or semi-analytical solutions for them. We plan on solving the TAC-2 types of problems using the following strategy. Westergaard [75] solved the normal contact problem between two elastic half-spaces having sinusoidal surfaces. Johnson [71] took Westergaard's solution and introduced adhesion using the Griffith crack-analogy method pioneered by Maugis [76]. England and Green [77] employed complex potential functions and solved the problem of normal contact between half-spaces having arbitrary wavy surfaces, i.e., the generalized version of the problem solved by Westergaard. We will use the method used by Johnson to introduce JKR type adhesion into the general solution given by England and Green [77]. This will allow us to solve what we term the NAC-2 problem, which is the problem of normal, adhesive, contact between half-spaces having arbitrarily wavy surfaces. We will use the solutions to a family of NAC-2 problems to solve the TAC-2 problem. This is possible because we have identified the following very important equivalence between the NAC-2 and TAC-2 problems. It can be shown that at each load step, all the fields in the TAC-2 problem can be derived from the solution of an equivalent new NAC-2 problem. The wavy profiles in the equivalent NAC-2 problem are equal to the sum and difference of the wavy profiles of the TAC-2 problem expressed in a coordinate frame attached to one of the half-spaces of the TAC-2 problem. In the TAC-2 problem, as the top half-space is translated, the description of the waviness of the top (or bottom) half-space in the reference frame of the bottom (resp. top) half-space continually changes. Thus, at different load steps the wavy profiles in the equivalent NAC-2 problem are different. The wavy profiles in the equivalent NAC-2 problem can be very complicated even when the wavy-profiles in the TAC-2 problem are simple. However, since we know how to solve the NAC-2 problem (combining the work of Johnson, and England and Green) for arbitrary pairs of wavy profiles, the equivalent NAC-2 problem can be solved at all load steps. We will simplify the solution of the TAC-2 problem to derive an equation of the form:

$$P_T = P_T(w, E \ldots, A \ldots, P_N; \lambda). \tag{2}$$

The ellipses in eq. (2) denote the other bulk elastic properties and dimensionless parameters defining the wavy profiles in the problem. The solution of the TAC-2 problem and the resulting eq. (2) will be checked using the computer simulations (see sec. 3.3 for details).

A1.T3: Asymptotic analysis of eq. (2)

We believe that the TAC-2 problem will show similar types of energy dissipating contact instabilities seen in the 2-sphere contact problem. However, the advantage of TAC-2 problems is that since the small-length scale parameter λ explicitly appears in eq. (2), we will be able to study whether the contact instabilities lead to the emergence of an effective frictional behavior at the large scale. We will be able to do so by analyzing the asymptotic behavior of eq. (2) as $\lambda/a \to 0$. The goal is to derive asymptotic relations of the form

$$\langle P_T \rangle \sim \Lambda \left(w, E \ldots, A \ldots, P_N; \lambda\right), \tag{3a}$$

or possibly,

$$\langle P_T \rangle \sim \mu_{\text{eff}} P_N, \tag{3b}$$

where $\mu_{\text{eff}} = \mu_{\text{eff}} \left(w, E \ldots, A \ldots\right)$, which hold as $\lambda/a \to 0$. Studying the asymptotic form of eq. (2) is the most challenging and delicate task of the proposed research. However, the PI has the required expertise for carrying out this task. He derived eqs. (1a)–(1b), which describe the emergence of hysteresis due to small-scale waviness, using a similar type of asymptotic analysis that we plan on using for deriving eqs. (3). Furthermore, the asymptotic analysis will be guided by our computer simulations. Using the computer simulations, we will be able to check whether or not the assumptions and approximations we will be making while carrying out the asymptotic analysis are correct.

3.3 A2, Computational modeling

A number of computational techniques have been used to study adhesive contact problems. They broadly fall into two categories: continuum mechanics-based techniques, the most popular of these being cohesive zone-based finite element method [31], and atomistic simulation techniques [78–82], such as molecular dynamics and statics. Sophisticated, hybrid "multi-scale" techniques that combine continuum and atomistic level modeling strategies are also being actively developed and used [83, 84]. We believe that despite the considerable computational resources available to us, the atomistic simulations would be too expensive in terms of the computation times involved for the purposes of the proposed project. We therefore will use continuum mechanics-based computational techniques in the proposed research.

The PI and his group have explored cohesive zone-based finite element techniques in the months leading up to the submission of this proposal for their suitability for the proposed project. For example, the solution of the transverse contact problem for the case of extremely small adhesion shown in Fig. 5 a was produced using cohesive zone-based finite element methods in Abaqus. When there are no contact instabilities involved (e.g., in the regime of small adhesion or large stiffness) we could produce reasonable results. However, in most other cases the nonlinear numerical solver could not converge at all load steps. We explored different strategies, including using continuation (arc-length) methods, for producing consistent convergence, but so far we have not been successful.

Body-force field contact technique A new continuum mechanics-based technique developed by the PI proved to be much more successful in capturing the adhesive contact instabilities. Consider the contact problems shown in Fig. 3. In the new technique, the contact interaction on the elastic solid is modeled as a spatial body force field created by the rigid solid. The body force is derived by assuming that each pair of material particles belonging to the elastic and rigid solids interact via the Lennard-Jones (LJ) [85, Ch. 1, p. 7] type potential, $V(r) = 4\epsilon\left[(\sigma/r)^{12} - \alpha(\sigma/r)^6\right]$, where r is the distance between the material particles, and ϵ and σ are energy and length scale parameters. The parameter α is a positive real number that dictates the relative magnitudes of the adhesive and repulsive components of the interaction.

In the new technique we consider finite deformation of the solids. In the preliminary version we assumed that the rigid solid is an infinite half-space with no surface waviness. This simplification allowed us to

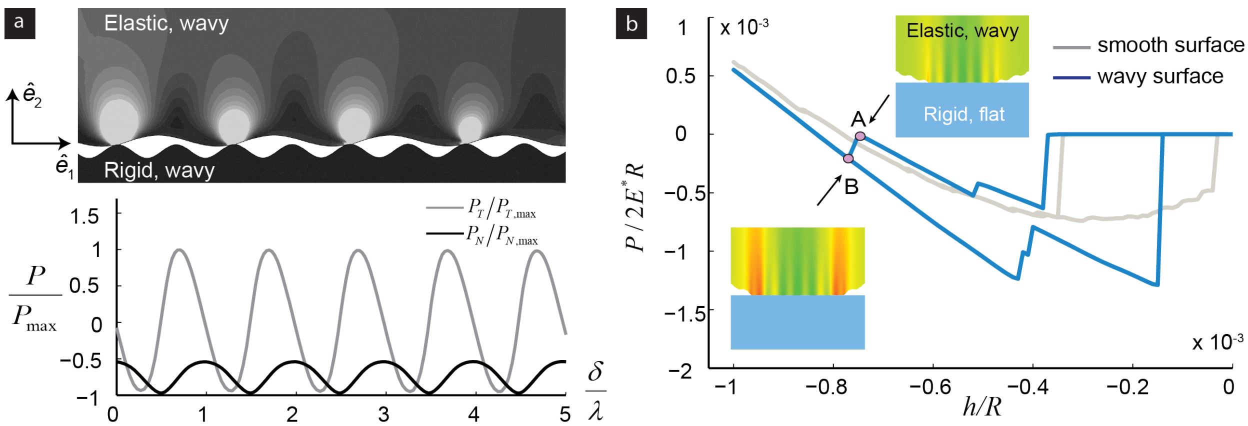

Figure 5: (a) Finite element simulation of adhesive contact between a wavy elastic solid and rigid substrate by using a cohesive zone model, Top: contour plot of normal stress σ_{22}, Bottom: The plot of change of P_T and P_N with moving distance δ. (b) Depth dependent hysteresis in P–h curves of the contact between an elastic tip (smooth and wavy surface) and a rigid substrate through body-force field-based contact simulations. Insets: Snapshots of the tip-substrate equilibrium configuration corresponding to the points A and B, which show the occurrence of an instability during the contact. The colors denote the deformation of tip in $-\hat{e}_2$ direction, with red denoting the maximum and blue the minimum.

integrate over the half-space and determine the expression for the total energy of an elastic particle with respect to the rigid solid. By differentiating that expression w.r.t to the elastic particle's Eulerian coordinates we obtained the body force, $(B_X\hat{\boldsymbol{e}}_1 + B_Y\hat{\boldsymbol{e}}_2)$, acting on the particle to be

$$B_Y = 4\pi\epsilon\sigma^2\rho^r\rho_0^e J^{-1}(\boldsymbol{X})\left[\frac{1}{2}\left(\frac{\sigma}{Y+u_Y}\right)^4 - \frac{1}{5}\left(\frac{\sigma}{Y+u_Y}\right)^{10}\right] \tag{4}$$

and $B_X = 0$, where Y and u_Y are the Lagrangian coordinate and displacement component of the elastic particle in the $\hat{e}_2$ direction, respectively. We take the elastic and rigid solids to be homogeneous, so the constants ρ^r, ρ_0^e are the densities of the rigid solid and the elastic solid (in the reference configuration), respectively. The parameter J is the Jacobian determinant of the deformation mapping, and $\boldsymbol{X}$ is the position vector of the elastic particle in the reference configuration. The results shown in Fig. 5 b were obtained by using a neo-Hookean material model for the elastic solid. The parameters σ and $\epsilon\rho^r\rho_0^e$ are chosen to be 0.001 and 1 $\mathrm{mJ/m^2}$, respectively. As can be see in Fig. 5 b the technique is able to capture contact instabilities extremely well.

However, for studying frictional effects it is important to include the waviness on the bottom solid, other wise P_T would always be zero. Our **Task A2.T1** therefore is to derive the body force field corresponding to an infinite half-space having surface waviness. Using the conformal mapping techniques used in [86], the wavy half-space can be mapped to a flat half-space. Therefore, we believe that we will be able to obtain a closed-form expression for the body force field corresponding to a wavy-half-space. **Task A2.T2** is to check the theoretical model developed through Task A1.T2, i.e., to specifically check the correctness of eq. (2). **Task A2.T3** is to guide the simplification of eq. (2) in the limit $\lambda/a \to 0$. Completion of task A2.T3 would also help us in interpreting our experimental measurements. **Task A2.T4** is to develop a generalized version of the new technique that is capable of handling arbitrary geometries for both solids and will allow both solids to be deformable. Completion of A2.T4 would allow us to use experimental measurements from literature to further test the veracity of H_0.

3.4 A3, Contact Mechanics Experiments

We propose to construct a mechanical testing stage (MTS, see Fig. 6 a) to perform contact mechanics experiments between rigid punches and compliant elastomeric substrates, such as PDMS. The punch and the elastomeric substrates will be brought into contact by moving the 3-axis stage in the normal direction. Forces in the normal and transverse directions will be measured as the punch is slid over the substrate. The force measurement principle in our apparatus is similar to that of an AFM [87] and the device used in [88].

In our MTS, the substrate sits on an elastically deformable beam structure. Deflection of the structure in the normal and transverse directions is measured using fiber optic sensors. The forces are computed using the beam's stiffnesses, which are measured using high precision calibration masses. For example, the structure shown in Fig. 6 b is designed to have a stiffness in the normal direction of $1690\,\mathrm{N/m}$. A number of devices similar to the proposed one are reported in literature. However, our MTS is custom designed to have a significantly higher capability compared to the earlier devices for collecting the data needed for our research. Its enhanced capability is due to the many innovations we have made in its design. We list three significant ones.

(i) Using high resolution 3D printing, we will manufacture punches that have a variety of wavy surface architectures (see Fig. 6 c). A sequence of punches will be made in which λ is slowly reduced, while keeping all other parameters (such as E, w) constant. Hence, we will be able to perform contact experiments in which the contact geometries and the loading conditions are almost exactly the same as the ones in our theoretical and computational contact models.

(ii) The length scales in the experiments using the proposed MTS will be small enough so that the adhesive forces are measurable and yet at the same time large enough so that it is easy to visualize the size and topology of the contact region. We are interested in the role of adhesive forces that arise naturally, that is from the van der Waals family of interactions. These interactions correspond to a work of adhesion of $25\,\mathrm{mJ/m^2}$. The effects of the van der Waals forces are easier to detect in experiments in which the size of the punches are below one millimeter (see [15]). The elastomeric materials we plan on working with have a Young's modulus of $\sim 2\,\mathrm{MPa}$. Thus we need to be able to measure forces $\sim 1\,\mathrm{N}$. Standard force sensors, such as those provided by Instron, are not suitable for the proposed research as they do not have sufficient resolution when measuring forces in the $\sim 1\,\mathrm{N}$ range. Nano-indentation systems can measure $\sim 1\,\mathrm{N}$ forces with high resolution. However, in the commercially available nano-indentation systems it is not possible to visualize the contact area during the contact experiments. Our MTS will be capable of measuring forces ranging from $27\,\mathrm{mN}$ to $3\,\mathrm{N}$ with resolutions of $18\,\mu\mathrm{N}$ and $2\,\mathrm{mN}$, respectively. Furthermore, we have designed a microscope into our MTS, which will allow us to measure $\sim 3\,\mathrm{mm}^2$ sized contact areas with $50\,\mu\mathrm{m}^2$ accuracy. Thus, our MTS has an ideal design for the purposes of the proposed research.

(iii) The AFM and the devices most related to our MTS [87] use a cantilever configuration for the force measuring beam structure (Fig. 6 d(i)). This configuration constrains the experiments to only using punches with hemispherical surfaces, since as the substrate and the punch make contact the relative orientation of the substrate and the punch changes (see Fig. 6 d(i)). That is, the substrate deformation contains a rigid body rotation component that makes it very difficult to model the experiment, even with computational techniques. The problem is automatically resolved for hemispherical punches. This is because, since a sphere looks the same from any direction, the substrate's rigid body rotation is equivalent to no-rotation when using a spherical punch. For non-spherical shapes the problem remains and cannot be circumvented by alternately placing the punch on the cantilever. Ignoring the rigid body rotation makes the modeling tractable, however, the associated error is small only if the forces are also small. Our MTS uses a double-fixed configuration for the force measuring beam structure (Fig. 6 b, d(ii)). Here, the substrate and the punch do not undergo any rigid body rotation relative to each other during the experiments (see Fig. 6 d(ii) for explanation). This allows us to use a wider variety of punches, such as those shown in Fig. 6 c, and operate at large forces. By slightly modifying the beam design we are able to perform experiments in a relatively unexplored parameter space. The double-fixed beam setup is used in nano indentation and other similar devices [89]. However, we believe that we are the first to propose taking advantage of it for performing experiments involving novel punch geometries.

3.5 A4, Project evaluation and conclusion

The final goal of the proposal is to derive the asymptotic behavior of eq. (2). The outcome of this analysis can vary depending on the nature of the equations. We discuss two potential scenarios below.

Scenario (a): The energy loss resulting from the contact instabilities remains finite as $\lambda/a \to 0$. In this case we will define the effective friction coefficient using eqs. (3). It will be interesting to study how μ_{eff} depends on E^*, w, and dimensionless surface waviness parameters. The μ_{eff} values predicted by our theory will be compared with our computer simulations and with the measurements from our experiments (sec. 3.4). The experiments will measure μ_{eff} on a family of surfaces that are very similar to the wavy surfaces analyzed in TAC-2 problems. If our predicted μ_{eff} values are supported by our computer simulations

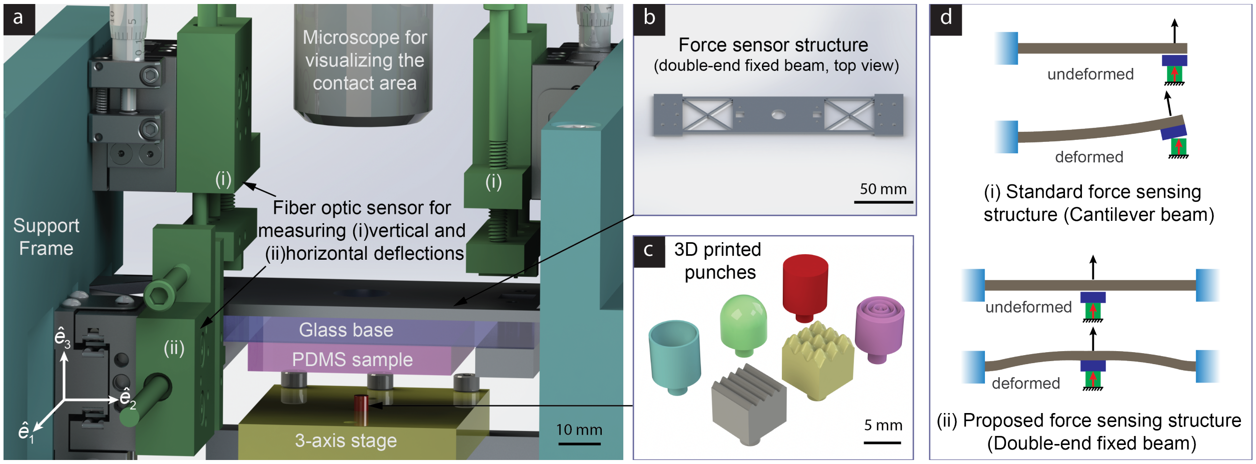

Figure 6: Experimental setup for adhesive contact studies: (a) CAD rendering of the MTS showing primary components, (b) Novel force sensor structure, (c) CAD rendering of punches with various surface shapes, which will be 3D printed, and (d) A schematic showing the advantage of double-fixed beams over cantilevers as force sensors.

and our experiments, we will be able to conclude that our hypothesis Ho is correct. That is, the friction behavior can emerge at the large scale primarily due to the adhesion and surface topography at the small scale. This would be a great scientific finding, for an elaboration of its significance see sec. 1.4.

Scenario (b): The energy loss vanishes as $\lambda/a \to 0$. In this case we will try to understand whether the vanishing of the energy loss is due to us restricting ourselves to wavy surfaces. This will done by performing computer simulations on other types of surfaces. If the simulations show that the energy loss also vanishes for a wide family of surfaces, then we will be able to conclude that the small-scale adhesion and architecture cannot be prime contributors to large-scale friction. That is, Ho is false. However, even in this case of negative results we believe that the theoretical techniques and the computational and experimental tools that will be developed over the course of the project will be very valuable to the mechanics community. With further development, these techniques and computational tools can be used for studying a wide variety of mechanics problems, such as contact problems involving elastic heterogeneity and interface fracture problems involving wavy interfaces. Even if small-scale adhesion is not directly related to the origin of friction, adhesive elastic contact remains important in its own right, as it plays a crucial role in a variety of tasks. These range from nanoprobing [90] and preventing stiction failure in micro/nanosystems [44], to understanding biological processes such as cell adhesion and migration [85], and recently, locomotion in geckos [91, 92].

Our response to other outcome scenarios will lie somewhere between our responses to scenarios (a) and (b).

4 Program management

Project time line: An approximate timeline of the proposed research is shown in Table 1.

Table 1: Project Time Line

Research tasks\Year	1	2	3
A1	A1.T1, A1.T2	A1.T3	
A2	A2.T1	A2.T2	A2.T3, A2.T4
A3		A3.T1	A3.T2
A4			A4.T1, A4.T2

Team and expertise: The research group will consist of the PI and a graduate student at Brown. The PI has worked on various adhesive contact mechanics problems since 2003 [43]. He has investigated the mechanics of adhesive elastic contact using both theory (asymptotic methods [3], variational principles [70]) and computations (finite element methods and molecular dynamics [15]). He also has expertise in measuring contact force-indentation curves using AFM and nano-indentation apparatus [2]. Based on his experience and the opportunity to work with outstanding student scholars in mechanics at Brown, the PI is confident that he will be able to produce many exciting results—some of which will be of great scientific value—by carrying out the proposed research successfully.

5 Broader impacts of the proposed work

The PI plans on integrating his research and educational programs through a broad range of educational outreach, and teaching activities. The details are as follows.

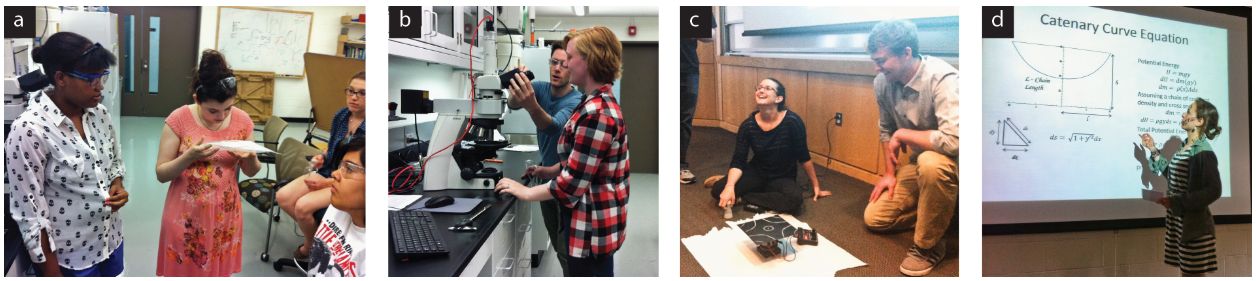

Figure 7: (a)–(b) SPIRA students and (c)–(d) undergraduates from PI's courses taking part in activities that were designed using the output from the PI's research program. The activities included several examples of how mechanics of materials research is enabling engineers solve critical societal problems.

Collaboration with the Sci-Toons initiative The PI will collaborate with the Sci-Toons initiative at Brown to create scientific cartoons on topics related to interesting contact mechanics phenomena in biological systems with a focus on bio- and nature-inspired engineering. Some examples of biological systems that display interesting contact mechanics phenomena were discussed in sec. 2.1 and Fig. 1. The Sci-Toons initiative is an informal science education program at Brown University's Science Center. Sci-Toon videos combine art, animation, high-quality multimedia and storytelling. In the Sci-Toons collaboration, the PI and his students will work with both STEM and non-STEM students, as well as animators in the development of the script, storyboard and science animation. Sci-Toons videos are a powerful tool for engaging and communicating scientific research and concepts to a broad audience. Through the effective use of "jargon-free" language and engaging storytelling, the Sci-Toons videos aim to get non-STEM majors interested in STEM subjects, STEM majors to appreciate the importance of scientific communication, and the general public to develop a greater understanding and appreciation of science. The Sci-Toons are distributed via a variety of social media platforms.

Through the collaboration, the PI will help create one Sci-Toon video per academic year for the next three years. The collaboration on the first video has already begun (in Spring 2015). The first video is titled "How Natural Evolution is Helping Engineers." The video will discuss how the idea of "survival of the fittest" results in biological structures/materials acquiring better and new properties through the accumulation of beneficial changes in their macro- and micro-scale structure. The video will discuss some of the close-to-optimal designs found in nature, and will give concrete examples of how those designs have inspired engineers and inventors (e.g. Velcro, Chipper Chain [93]). The video will end by highlighting the fact that the vast majority of nature's designs remain unknown to engineers, and excite the viewers about the immense possibilities that the discovery of such designs would create for science and engineering.

The Sci-Toon creation group consists of both STEM and non-STEM students and faculty. Funds to support the PI's collaboration with the Sci-Toons initiative are requested as part of the budget (see Budget Justification). *Evaluation:* The impact of the Sci-Toon videos will be gauged by monitoring the number and geographic distribution of the views that the videos generate. Some of the past Sci-Toons videos have been viewed in over 70 countries. Examples of completed Sci-Toons can be viewed on the Sci-Toon YouTube channel at [94], and more information on the Sci-Toons initiative can be found at [95].

Nature's Ingenious Designs (NID) competition and podcast The PI will also post the Sci-Toons videos on his lab website. The website will be set up so that the viewers can post comments and questions about the videos. These comments and questions will be discussed and answered in the NID podcast described below.

The Sci-Toon videos will encourage the viewers to participate in the NID competition that will be started by the PI in Fall 2016. As part of the competition, the participants will be asked to identify a biological construction (material or structure) that displays a strong potential for the discovery of new engineering designs or principles. The participants will be asked to submit a less than 5 minute video clip in which they make their case for why the biological construction that they have identified is a good candidate for conducting mechanics investigations.

The NID competition is aimed at addressing a critical bottleneck faced by the mechanics community that is interested in bio-inspired engineering. There has been interest in the topic of of discovering new mechanics principles by studying nature and biology for the past several decades; however, this research direction has not matured as an engineering subject. The PI believes that identifying good candidate biological materials/structures for conducting mechanics investigations is the critical bottleneck holding it back. Historically, in most cases of bio- and nature-inspired discoveries, the designs/principles were recognized in the biological systems primarily by chance (consider again the examples of Velcro or the Chipper Chain [93]). There is currently no protocol for identifying good candidate biological materials/structures for conducting mechanics investigations. The PI believes that organizing the NID competition would contribute to the creation of such a protocol. *Evaluation:* The final discussion session in which the top three winning entries are selected will be recorded and aired as a NID podcast. The winning entries will be awarded a cash prize. The competition results, links to the podcast, and the wining videos will all be posted to the PI's website that hosts the original Sci-Toon video. Funds for organizing the NID competition and podcast are requested as part of the budget.

Collaboration with SPIRA SPIRA is a four week camp hosted by Brown every summer for high school-age girls to explore engineering. The PI and his students have been collaborating with SPIRA in order to encourage young women to pursue education in STEM fields by exposing them to interesting applications of engineering. The camp is free to those who attend and often attracts students from underrepresented minorities. The graduate student who will be involved in the proposed research (Max Monn) has been collaborating with SPIRA for the last three years as an invited speaker. Pictures from some past SPIRA activities that were conducted by the PI's group in his lab are shown in Fig. 7. Over the course of the proposed project, the PI will help Max Monn design new talks and tutorials for the SPIRA participants that will highlight the importance of contact mechanics and bio-inspired engineering. As part of the project a new contact mechanics related activity called the *The Incredible Insect-Man* competition will be organized for the SPIRA students. In the competition the participants will be challenged to construct a $\mathrm{mm}{-}\mathrm{cm}$ size adhesive/attachment structure that is inspired by the different mechanisms through which insects (e.g., flys, ants) adhere and scale vertical surfaces. The effectiveness of the students' structures will be gauged by the range of surfaces that the structures can adhere to, and the maximum weights that they can support. The student teams will be supplied with various materials and given access to the microscope, and the micro-manipulation tools in the PI's lab. Funds to organize this new competition in collaboration with SPIRA are requested as part of the budget. *Evaluation:* The effectiveness of the planned SPIRA lectures, tutorials, and competitions will be gauged using exit interviews. The students' feedback will also be solicited by encouraging them to post comments and suggestions on the SPIRA section of the PI's website. The questions in the exit interviews and the website will be designed to determine which activities, and what aspects of them, the participants found most engaging and useful and to determine how the activities can be further improved in the future.

6 Results from prior NSF support

None.

References Cited

[1] D. Maugis. *Contact Adhesion and Rupture of Elastic Solids*. Solid State Sciences. Springer, 2000.

[2] H. Kesari, J. Doll, B. Pruitt, C. Wei, and A. Lew. The Role of Surface Roughness During Adhesive Elastic Contact. *Philosophical Magazine Letters*, 90(12):891–902, 2010.

[3] Haneesh Kesari and Adrian J Lew. Effective macroscopic adhesive contact behavior induced by small surface roughness. *Journal of the Mechanics and Physics of Solids*, 59(12):2488–2510, 2011.

[4] Bharat Bhushan. Biomimetics: lessons from nature–an overview. *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences*, 367(1893):1445–1486, 2009.

[5] Photo by Sandra Prietz.

[6] D Whittaker. Beacon researchers at work: How do geckos stick to the wall? http://beacon-center.org/wp-content/uploads/2011/11/Pic3.jpg, 2011. [Online; accessed 1-July-2014].

[7] BC Tørrissen. Gecko foot on glass. http://en.wikipedia.org/wiki/Synthetic_setae#mediaviewer/File:Gecko_foot_on_glass.JPG, 2009. [Online; accessed 1-July-2014].

[8] W Federle, WJP Barnes, W Baumgartner, P Drechsler, and JM Smith. Wet but not slippery: boundary friction in tree frog adhesive toe pads. *Journal of The Royal Society Interface*, 3(10):689–697, 2006.

[9] M Avellaneda, Andrej V Cherkaev, KA Lurie, and Graeme W Milton. On the effective conductivity of polycrystals and a three-dimensional phase-interchange inequality. *Journal of applied physics*, 63(10):4989–5003, 1988.

[10] Moulinec H. Michel, J.C. and P. Suquet. Effective properties of composite materials with periodic microstructure: a computational approach. *Computer methods in applied mechanics and engineering*, 172(1):109–143, 1999.

[11] Geers M. G. Kouznetsova, V. and W. M. Brekelmans. Multi-scale constitutive modelling of heterogeneous materials with a gradient-enhanced computational homogenization scheme. *International Journal for Numerical Methods in Engineering*, 54(8):1235–1260, 2002.

[12] Pedro Ponte Castañeda. Second-order homogenization estimates for nonlinear composites incorporating field fluctuations: I-theory. *Journal of the Mechanics and Physics of Solids*, 50(4):737–757, 2002.

[13] L Capolungo, C Jochum, M Cherkaoui, and J Qu. Homogenization method for strength and inelastic behavior of nanocrystalline materials. *International Journal of Plasticity*, 21(1):67–82, 2005.

[14] Jerry L Ericksen, David Kinderlehrer, Robert Kohn, and J-L Lions. *Homogenization and effective moduli of materials and media*, volume 1. Springer Science & Business Media, 2012.

[15] H. Kesari. *Mechanics Of Hysteretic Adhesive Elastic Mechanical Contact Between Rough Surfaces*. PhD thesis, Stanford University, 2011.

[16] P Mohammadi, LP Liu, P Sharma, and RV Kukta. Surface energy, elasticity and the homogenization of rough surfaces. *Journal of the Mechanics and Physics of Solids*, 61(2):325–340, 2013.

[17] H. Hertz. On the contact of elastic solids. *J. Reine Angew. Math.*, 92:156–171, 1881.

[18] K. L. Johnson, K. Kendall, and A. D. Roberts. Surface energy and the contact of elastic solids. *Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences*, 324(1558):301–313, 1971.

[19] B. V. Derjaguin, V. M. Muller, and Yu. P. Toporov. Effect of contact deformations on the adhesion of particles. *Journal of Colloid and Interface Science*, 53(2):314–326, November 1975.

[20] D. Maugis. Adhesion of spheres: the JKR-DMT transition using a dugdale model. *Journal of colloid and interface science*, 150(1):243–269, 1992.

[21] Feodor M Borodich and Boris A Galanov. Self-similar problems of elastic contact for non-convex punches. *Journal of the Mechanics and Physics of Solids*, 50(11):2441–2461, 2002.

[22] G Carbone and F Bottiglione. Asperity contact theories: Do they predict linearity between contact area and load? *Journal of the Mechanics and Physics of Solids*, 56(8):2555–2572, 2008.

[23] M Ciavarella. Transition from stick to slip in hertzian contact with "griffith" friction: the cattaneo-mindlin problem revisited. *Journal of the Mechanics and Physics of Solids*, 2015.

[24] A Papangelo, M Ciavarella, and JR Barber. Fracture mechanics implications for apparent static friction coefficient in contact problems involving slip-weakening laws. In *Proc. R. Soc. A*, volume 471, page 20150271. The Royal Society, 2015.

[25] John Dolbow, Nicolas Moës, and Ted Belytschko. An extended finite element method for modeling crack growth with frictional contact. *Computer Methods in Applied Mechanics and Engineering*, 190(51):6825–6846, 2001.

[26] L Pei, S Hyun, JF Molinari, and Mark O Robbins. Finite element modeling of elasto-plastic contact between rough surfaces. *Journal of the Mechanics and Physics of Solids*, 53(11):2385–2409, 2005.

[27] Roger Andrew Sauer. *An atomic interaction based continuum model for computational multiscale contact mechanics*. PhD thesis, University of California, Berkeley, 2006.

[28] Chunyan Yang and BNJ Persson. Molecular dynamics study of contact mechanics: contact area and interfacial separation from small to full contact. *Physical review letters*, 100(2):024303, 2008.

[29] Vladislav A Yastrebov, Julian Durand, Henry Proudhon, and Georges Cailletaud. Rough surface contact analysis by means of the finite element method and of a new reduced model. *Comptes Rendus Mécanique*, 339(7):473–490, 2011.

[30] C Putignano, L Afferrante, G Carbone, and G Demelio. A new efficient numerical method for contact mechanics of rough surfaces. *International Journal of Solids and Structures*, 49(2):338–343, 2012.

[31] M Elices, GV Guinea, J Gomez, and J Planas. The cohesive zone model: advantages, limitations and challenges. *Engineering fracture mechanics*, 69(2):137–163, 2002.

[32] JM Haile. *Molecular dynamics simulation*, volume 18. Wiley, New York, 1992.

[33] Isaak Abramovich Kunin. *Elastic media with microstructure I: one-dimensional models*, volume 26. Springer Science & Business Media, 2012.

[34] D. A. Hill, D. Nowell, and A. Sackfield. *Mechanics of Elastic Contact*. Butterworth Heinemann, 1993.

[35] Zhanjiang Wang, Xiaoqing Jin, Leon M Keer, and Qian Wang. Novel model for partial-slip contact involving a material with inhomogeneity. *Journal of Tribology*, 135(4):041401, 2013.

[36] Peijian Chen and Shaohua Chen. Partial slip contact between a rigid punch with an arbitrary tip-shape and an elastic graded solid with a finite thickness. *Mechanics of Materials*, 59:24–35, 2013.

[37] IL Singer. Friction and energy dissipation at the atomic scale: A review. *Journal of Vacuum Science & Technology A*, 12(5):2605–2616, 1994.

[38] T Filleter, Jessica L McChesney, Aaron Bostwick, Eli Rotenberg, KV Emtsev, Th Seyller, Karsten Horn, and R Bennewitz. Friction and dissipation in epitaxial graphene films. *Physical review letters*, 102(8):086102, 2009.

[39] Srivatsan Hulikal Sampath Kumaran. *Collective behavior of asperities as a model for friction and adhesion*. PhD thesis, California Institute of Technology, 2015.

[40] K Autumn, A Dittmore, D Santos, M Spenko, and M Cutkosky. Frictional adhesion: a new angle on gecko attachment. *Journal of Experimental Biology*, 209(18):3569–3579, 2006.

[41] Shravanthi Reddy, Eduard Arzt, and Aranzazu del Campo. Bioinspired surfaces with switchable adhesion. *Advanced Materials*, 19(22):3833–3837, 2007.

[42] Joseph M Romano, Kaijen Hsiao, Günter Niemeyer, Sachin Chitta, and Katherine J Kuchenbecker. Human-inspired robotic grasp control with tactile sensing. *Robotics, IEEE Transactions on*, 27(6):1067–1079, 2011.

[43] Haneesh Kesari and Suhas S. Mohite. Vibration analysis of a collapsed mems microbeam for measuring the work of adhesion. In *Workshop Digest of the 15th MicroMechanics Europe Workshop (MME '04), Leuven, Belgium*, pages 88–91, 2004.

[44] F.W. DelRio, M.P. de Boer, J.A. Knapp, E.D. Reedy Jr, P.J. Clews, and M.L. Dunn. The role of van der Waals forces in adhesion of micromachined surfaces. *Nature Materials*, 4:629–634, 2005.

[45] Yiğit Mengüç, Sang Yoon Yang, Seok Kim, John A Rogers, and Metin Sitti. Gecko-inspired controllable adhesive structures applied to micromanipulation. *Advanced Functional Materials*, 22(6):1246–1254, 2012.

[46] Matthew A Meitl, Zheng-Tao Zhu, Vipan Kumar, Keon Jae Lee, Xue Feng, Yonggang Y Huang, Ilesanmi Adesida, Ralph G Nuzzo, and John A Rogers. Transfer printing by kinetic control of adhesion to an elastomeric stamp. *Nature Materials*, 5(1):33–38, 2006.

[47] Mark R Cutkosky. Climbing with adhesion: from bioinspiration to biounderstanding. *Interface Focus*, 5(4):20150015, 2015.

[48] W. Barthlott and C. Neinhuis. Purity of the sacred lotus, or escape from contamination in biological surfaces. *Planta*, 202(1):1–8, 1997.

[49] Yang T Cheng, DE Rodak, CA Wong, and CA Hayden. Effects of micro-and nano-structures on the self-cleaning behaviour of lotus leaves. *Nanotechnology*, 17(5):1359, 2006.

[50] Li Wen, James C Weaver, and George V Lauder. Biomimetic shark skin: design, fabrication and hydrodynamic function. *The Journal of experimental biology*, 217(10):1656–1666, 2014.

[51] K. Autumn, Y.A. Liang, S.T. Hsieh, W. Zesch, W.P. Chan, T.W. Kenny, R. Fearing, and R.J. Full. Adhesive force of a single gecko foot-hair. *Nature*, 405(6787):681–685, 2000.

[52] H. Gao and H. Yao. Shape insensitive optimal adhesion of nanoscale fibrillar structures. *Proceedings of the National Academy of Sciences of the United States of America*, 101(21):7851, 2004.

[53] Dirk-Michael Drotlef, Lukas Stepien, Michael Kappl, W Jon P Barnes, Hans-Jürgen Butt, and Aranzazu del Campo. Insights into the adhesive mechanisms of tree frogs using artificial mimics. *Advanced Functional Materials*, 23(9):1137–1146, 2013.

[54] G.A.D. Briggs and B.J. Briscoe. Effect of surface roughness on rolling friction and adhesion between elastic solids. *Nature*, 260(5549):313–315, 1976.

[55] William D Callister and David G Rethwisch. *Fundamentals of materials science and engineering: an integrated approach*. John Wiley & Sons, 2012.

[56] Kevin C Nunan and Joseph B Keller. Effective elasticity tensor of a periodic composite. *Journal of the Mechanics and Physics of Solids*, 32(4):259–280, 1984.

[57] S Nemat-Nasser, T Iwakuma, and M Hejazi. On composites with periodic structure. *Mechanics of materials*, 1(3):239–267, 1982.

[58] Graeme W Milton. *The theory of composites*, volume 6. Cambridge university press, 2002.

[59] E Weissenbek, Helmut J Böhm, and Franz G Rammerstorfer. Micromechanical investigations of arrangement effects in particle reinforced metal matrix composites. *Computational materials science*, 3(2):263–278, 1994.

[60] P Ponte Castañeda. Exact second-order estimates for the effective mechanical properties of nonlinear composite materials. *Journal of the Mechanics and Physics of Solids*, 44(6):827–862, 1996.

[61] J Cho, MS Joshi, and CT Sun. Effect of inclusion size on mechanical properties of polymeric composites with micro and nano particles. *Composites Science and Technology*, 66(13):1941–1952, 2006.

[62] M. Urbakh, J. Klafter, D. Gourdon, and J. Israelachvili. The nonlinear nature of friction. *Nature*, 430(6999):525–528, 2004.

[63] N. Maeda, N. Chen, M. Tirrell, and J.N. Israelachvili. Adhesion and friction mechanisms of polymer-on-polymer surfaces. *Science*, 297(5580):379–382, 2002.

[64] YL Chen, CA Helm, and JN Israelachvili. Molecular mechanisms associated with adhesion and contact angle hysteresis of monolayer surfaces. *Journal of Physical Chemistry*, 95:10736–10746, 1991.

[65] H. She, D. Malotky, and M.K. Chaudhury. Estimation of adhesion hysteresis at polymer/oxide interfaces using rolling contact mechanics. *Langmuir*, 14(11):3090–3100, 1998.

[66] S.M. Rubinstein, G. Cohen, and J. Fineberg. Contact area measurements reveal loading-history dependence of static friction. *Physical Review Letters*, 96(25):256103, 2006.

[67] M.K. Chaudhury. Interfacial interaction between low-energy surfaces. *Materials Science & Engineering R*, 16(3):97–159, 1996.

[68] JP Pickering, DW Van Der Meer, and GJ Vancso. Effects of contact time, humidity, and surface roughness on the adhesion hysteresis of polydimethylsiloxane. *Journal of Adhesion Science and Technology*, 15(12):1429–1441, 2001.

[69] G.Y. Choi, S. Kim, and A. Ulman. Adhesion hysteresis studies of extracted poly(dimethylsiloxane using contact mechanics). *Languir*, 13:6333–6338, 1997.

[70] H. Kesari and A.J. Lew. Adhesive Frictionless Contact Between an Elastic Isotropic Half-Space and a Rigid Axi-Symmetric Punch. *Journal of Elasticity*, 2011. DOI: 10.1007/s10659-011-9323-8.

[71] KL Johnson. The adhesion of two elastic bodies with slightly wavy surfaces. *International Journal of Solids and Structures*, 32(3):423–430, 1995.

[72] Mikhail Nosonovsky and George G Adams. Dilatational and shear waves induced by the frictional sliding of two elastic half-spaces. *International journal of engineering science*, 39(11):1257–1269, 2001.

[73] George G Adams. Adhesion at the wavy contact interface between two elastic bodies. *Journal of applied mechanics*, 71(6):851–856, 2004.

[74] Joseph Block and Leon Keer. Periodic contact problems in plane elasticity. *Journal of Mechanics of Materials and Structures*, 3(7):1207–1237, 2008.

[75] HM Westergaard. Bearing pressures and cracks. *Journal of applied mechanics*, 6(2):A49–A53, 1939.

[76] D. Maugis, M. Barquins, and R. Courtel. Griffith cracks and adhesion of elastic solids. *Metaux-Corrosion-Industrie*, (605):1–10, 1976.

[77] AH England and AE Green. Some two-dimensional punch and crack problems in classical elasticity. In *Mathematical Proceedings of the Cambridge Philosophical Society*, volume 59, pages 489–500. Cambridge Univ Press, 1963.

[78] Uzi Landman, W. D. Luedtke, Nancy A Burnham, and Richard J. Colton. Atomistic mechanisms and dynamics of adhesion, nanoindentation and fracture. *Science*, 248(4954):454–461, 1990.

[79] Uzi Landman, W. D. Luedtke, and Jianping Gao. Atomic-scale issues in tribology: Interfacial junctions and nano-elastohydrodynamics. *Langmuir*, 12:4514–4528, 1996.

[80] T Trevethan and L Kantorovich. Atomistic simulations of the adhesion hysteresis mechanism of atomic scale dissipation in non-contact atomic force microscopy. *Nanotechnology*, 15:S34–S39, 2004.

[81] B. Luan and M.O. Robbins. The breakdown of continuum models for mechanical contacts. *Nature(London)*, 435(7044):929–932, 2005.

[82] Ju Li, Krystyn J. Van Vliet, Ting Zhu, Sidney Yip, and Subra Suresh. Atomistic mechanisms governing elastic limit and incipient plasticity in crystals. *Letters to Nature*, 418:307–310, July 2002.

[83] C. Yang, U. Tartaglino, and B. N. J. Persson. A multiscale molecular dynamics approach to contact mechanics. January 2006.

[84] Guillaume Anciaux, Srinivasa Babu Ramisetti, and Jean-François Molinari. A finite temperature bridging domain method for md-fe coupling and application to a contact problem. *Computer Methods in Applied Mechanics and Engineering*, 205:204–212, 2012.

[85] J.N. Israelachvili. *Intermolecular and surface forces*. Academic Press London, second edition, 1992.

[86] Tanaka H. A conformal mapping of a finite region bounded by wavy walls. *Proc. Jpn. Soc. Civil. Engrs.*, (369):319–322, 1986.

[87] Akihiro Torii, Minoru Sasaki, Kazuhiro Hane, and Shigeru Okuma. A method for determining the spring constant of cantilevers for atomic force microscopy. *Measurement Science and Technology*, 7(2):179, 1996.

[88] JF Waters. *Contact mechanics of biologically-inspired interface geometries*. PhD thesis, Brown University, 2009.

[89] Sauri Gudlavalleti. Mechanical testing of solid materials at the micro-scale, 2002.

[90] O. Sahin, S. Magonov, C. Su, C.F. Quate, and O. Solgaard. An atomic force microscope tip designed to measure time-varying nanomechanical forces. *Nature*, 2:507–514, 2007.

[91] H Yao and H Gao. Mechanics of robust and releasable adhesion in biology: Bottom–up designed hierarchical structures of gecko. *Journal of the Mechanics and Physics of Solids*, 54(6):1120–1146, 2006.

[92] H Gao, X Wang, H Yao, S Gorb, and E Arzt. Mechanics of hierarchical adhesion structures of geckos. *Mechanics of Materials*, 37(2):275–285, 2005.

[93] D DeYoung and D Hobbs. *Discovery of Design*. Master Books, 2009.

[94] Brown Science Center SciToons. https://www.youtube.com/user/scitoons. https://www.youtube.com/user/SciToons, 2015. [Online; accessed 10-July-2015].

[95] OO Adetunji. New directions in broader impacts – communicating scientific research through science cartoons (Sci-Toons). http://www.broaderimpacts.net/files/poster_D_Tools_Brown_Adetunji_SciToons_BII2014.pdf, 2015. [Online; accessed 10-July-2015].