Interactive Mesh-Free Stress Analysis for Mechanical Design Assembly With Haptics

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Abstract
This paper describes a virtual reality application that performs fast stress reanalysis coupled with virtual reality and haptics that allows rapid evaluation of multiple designs throughout the product design process. The Interactive Virtual Design Application (IVDA) allows the engineer to interactively explore new design geometry while simultaneously examining the finite element analysis results. In the presence of other parts in the assembly, the new shape can be analyzed and modified, taking into consideration mating part fits. This approach supports concurrent product design and assembly methods prototyping. A "two-step" approach utilizing Taylor series approximations and Pre-conditioned Conjugate Gradient methods is used to perform quick reanalysis during interactive shape modification. The virtual environment provides an immersive three-dimensional workspace. Haptics are used to provide feedback of the stress gradient as the part geometry is changed, thus facilitating the designer's understanding of the impact of shape change on product performance.

Keywords
VRAC, Manufacturing, Stress analysis (Engineering), Design engineering, Haptic interfaces

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INTERACTIVE MESH-FREE STRESS ANALYSIS FOR MECHANICAL DESIGN ASSEMBLY WITH HAPTICS

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ABSTRACT

This paper describes a virtual reality application that performs fast stress reanalysis coupled with virtual reality and haptics that allows rapid evaluation of multiple designs throughout the product design process. The Interactive Virtual Design Application (IVDA) allows the engineer to interactively explore new design geometry while simultaneously examining the finite element analysis results. In the presence of other parts in the assembly, the new shape can be analyzed and modified, taking into consideration mating part fits. This approach supports concurrent product design and assembly methods prototyping. A "two-step" approach utilizing Taylor series approximations and Pre-conditioned Conjugate Gradient methods is used to perform quick reanalysis during interactive shape modification. The virtual environment provides an immersive three-dimensional workspace. Haptics are used to provide feedback of the stress gradient as the part geometry is changed, thus facilitating the designer's understanding of the impact of shape change on product performance.

Keywords: Mesh-free analysis, Virtual Reality, Subdivision Volumes, Human Computer Interaction, Virtual Assembly, Mechanical Design.

INTRODUCTION

Virtual Reality (VR), through the use of stereo viewing and position tracking, allows participants to use natural human motions to interact with computer models in a 3D space [1]. Although VR is being used in the mechanical design process for prototype evaluation and assembly methods prototyping [2, 3], its application to analysis evaluation in the design process has not been fully explored. Throughout the product design process it is common to perform multiple stress analyses to verify the performance of the design. These analyses are usually performed in the later stages of design due to the extensive preprocessing and analysis time required obtaining a single solution. The most common result of the stress analysis is the need to change the part geometry; however, if this is discovered late in the design process, the proposed changes can be prohibitively expensive. By combining the powerful tools of VR and FEA, these performance evaluations can be performed earlier in the design cycle, before product geometry is fixed, thus resulting in better designs.

The objective of this research is to develop a method whereby a designer can utilize analysis results early in the design process before major decisions about product form are irreversibly made. In order to create such a process, fast analysis computational methods are needed. In addition, the ability to visualize the effect of shape changes on stress patterns facilitates increased understanding of the relationship between product shape and performance. In this work, computer models are coupled with analysis models, allowing shape and design changes to be performed in real-time with fast stress analyses and re-analyses, all within a three-dimensional virtual environment [4]. Haptic feedback, which allows the user to "feel" stress change while shape changes occur, is utilized as an additional aid to guide the designer.

BACKGROUND

In 1998 Yeh and Vance [5] were the first to combine virtual reality with free form deformation to perform interactive stress analysis in virtual reality. They used linear Taylor series approximations based on pre-computed stress sensitivities and a rectangular Non-Uniform Rational B-Spline (NURBS) bounding volume to deform the part shape. This first approach was limited by the accuracy of the Taylor series for large design changes and the need to perform a stress and sensitivity analysis before the virtual reality interaction could begin. In addition, the boundary volumes had to be specified beforehand, limiting the interaction between the user and the models. Figures 1 and 2 show a connecting rod with the corresponding volume and its deformed shape.

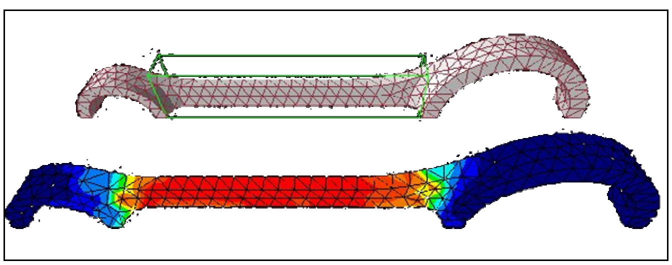

Figure 1: Initial configuration of a connecting rod with bonding volume visible [5].

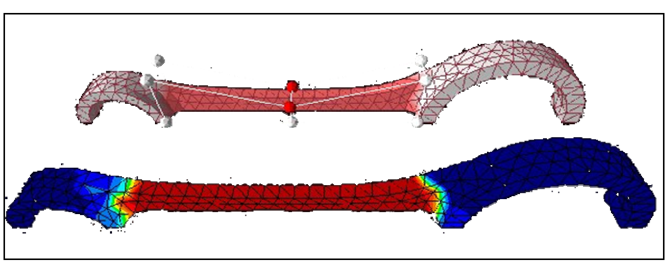

Figure 2: Deformed connecting rod with Taylor series stress approximations [5].

Ryken and Vance [6] then applied these techniques to a practical design problem. A tractor rear lift arm was experiencing high stress levels, but shape changes were severely limited because of potential interference with the lift assembly. Although interactively changing the shape was demonstrated as a feasible method, the user was still constrained by the need to determine the stress sensitivities and area to be changed before the application started.

Chipperfield et al. [7] implemented a pre-conditioned conjugate gradient (PCG) re-analysis method to accurately compute the stress contours resulting from design changes rapidly. This removed the need to calculate sensitivities prior to entering the virtual environment. Although the calculations were more accurate for large changes than the previous approach, which used only Taylor series approximations, the new method was still too slow for interactive design. As a result, a two-state process was developed. The Taylor series approximations were used for real-time stress updates as the user is changing the shape in the virtual environment, while the PCG method allows for a more accurate reanalysis after the interactive changing is completed. New stress sensitivities are calculated between major design changes as the user is examining the results of the analysis. Chipperfield also implemented a mesh free solver to allow for larger design changes. Due to the instability of finite element meshes at large deformations, the mesh-free method was selected to provide more flexibility on changing the model shape [8]. A reproducing kernel mesh-free analysis was used to compute the stress results [9]. Remeshing the finite element mesh is time prohibitive, therefore the mesh-free method was chosen.

INTERACTIVE VIRTUAL DESIGN APPLICATION

Interactive Virtual Design Application (IVDA) is a program that has been developed to test the interactive stress analysis approach. An initial finite element model is used to define the part geometry and to place the mesh-free nodes. This model is usually generated using ABAQUS or other commercially available pre-processors. The application performs an initial stress analysis and sensitivity calculation for selected control points. The user then defines a bounding volume around the part to identify the allowable deformation area by selecting two points in space. The volume is changed with wand movement once the first point is selected until a second is placed. To change the control point density, the volume may be repeatedly subdivided in any of the box's local coordinate directions. Multiple rubber-banded volumes may be used on a single model as well, in case several areas of interest arise. A designer can use the wand or the PHANTOM to modify the model, select different control points, change bounding volumes, and explore the shape change effects on the part in question (see Figure 3) [10].

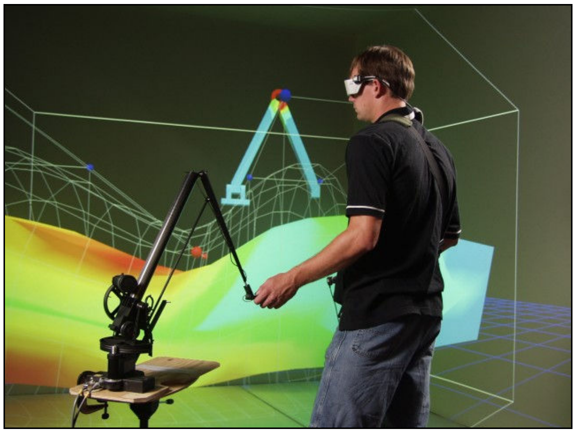

Figure 3: A user working with IVDA

Enabling collision detection allows the designer to change the design, while not allowing the models to interfere or intersect with each other [11]. By adding the ability to perform collision detection, several models can be analyzed at once and assembled.

Throughout the development of this method, the human computer interaction, where the user interactively changes the shape in the virtual environment, was a very important consideration. Yeh's method of using a NURBS volume as the control volume worked well for regular geometric shapes. In this current version, Fischer implemented the Catmull-Clark subdivision volume method which provides the user with more flexibility to define volumes of arbitrary shape and combine several volumes. Figure 4 shows several subdivided bounding volumes applied to a model.

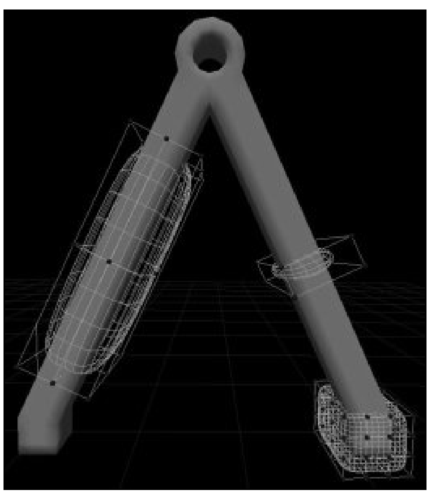

Figure 4: Subdivided bounding volumes around a model in the virtual environment.

Several mesh-free solvers have been explored and evaluated [12]. In the current implementation, an open source software package, Tahoe, was selected to be the mesh-free solver. Tahoe is a large open source project with support for many different elements, material models, and analysis types. It supports mesh-free methods, crack analysis, cohesive models and a number of other more specialized features [13].

Tahoe's implementation uses the reproducing kernel particle method (RKPM) with strain smoothing stabilization, introduced by Chen et al [14]. The RKPM is used to approximate unknown displacements in terms of the displacement coefficients at the mesh-free nodes. The displacement is defined as:

$$u^h(\mathbf{x}) = \sum_{I=1}^{N} \Psi_I(\mathbf{x})\ d_I \qquad \text{Eq. 1}$$

where $u^h(x)$ is the displacement, $\Psi_I(x)$ is the reproducing kernel shape function evaluated at the point x, with respect to the I^{th} node, and d_I are the displacement coefficients. Furthermore, the strain is defined as:

$$\boldsymbol{\varepsilon}^h(\mathbf{x}_L) = \sum_{I \in G_L} \mathbf{B}_I(\mathbf{x}_L)\mathbf{d}_I \qquad \text{Eq. 2}$$

where $\boldsymbol{\varepsilon}^h(x_L)$ is the strain at node L, $\mathbf{B}_I$, the smoothed strain gradient matrix; and d_I, the vector of displacement coefficients for node I. The function $u^h(x)$ is approximated using the surrounding particles using RKPM shape functions. The validity of mesh-free methods has been shown in numerous books and journals and will not be discussed here. Mesh-free methods allow large deformations, while traditional finite element methods become unstable. Mesh-free methods may require longer computation time than finite elements to compute, but can handle the deformations occurring in IVDA.

Haptic or force feedback has been provided to the user in the virtual environment through the use of a SensAble Technology PHANTOM [15]. Figure 5 shows the PHANTOM haptic device located on a movable and adjustable stand [11]. The PHANTOM is designed to be a desktop device. However, in this case, a stand allows the designer to explore the design space in a projection screen environment. The stand rolls on four castor wheels, and is tracked with a magnetic tracking device so that its position in the environment can be determined.

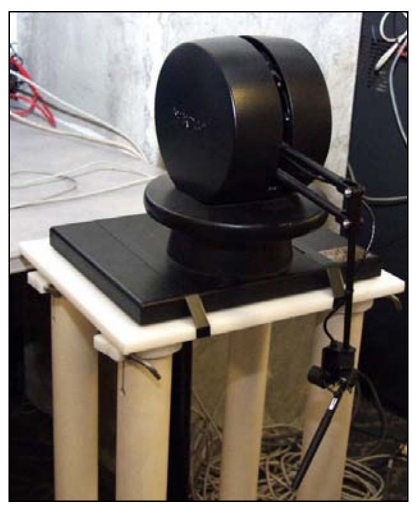

Figure 5: PHANTOM haptic device

Haptic feedback devices may prove to be essential components of virtual environments. In this case, the haptic force is proportional to the stress in the elements in the area of the haptic cursor. Stress information was modeled as a linear spring force, with higher stresses modeled with higher stiffness spring forces. In this application, the user will not feel more force or resistance when performing tight assembly operations. The haptic device is used to move the parts in space and to "feel" stress increases or decreases during shape changes. Haptic feedback comes into play when the user is deforming the models. It is harder to deform the model if the stresses become larger as a result of deformation. Therefore, creating higher stresses results in higher force feedback, and the engineer will follow the path of "least resistance" to find a better design.

The ability to interactively assembly parts depends on accurate collision detection. In this application, the OPCODE (Optimized Collision Detection) library is used [16]. OPCODE allows for colliding deformable meshes which are well suited for this work. The haptic device does recognize collisions and does not allow the user to intersect models when collision detection is enabled. This feature is very useful when testing assembly operations with models that may intersect. Because of the need for 1000 Hz haptic rates, a separate computer was used to drive the PHANTOM and this computer was networked with the cluster driving the application [19, 20].

The application was developed using the VRJuggler open source software toolkit (www.vrjuggler.org). VRJuggler provides an application interface that supports a wide variety of display devices [17, 18]. Therefore, with only small changes to an input file, this application can run on a desktop monitor, one wall projection screen, multiple wall projection screens or a head mounted display. ABAQUS was used to perform the initial finite element analysis. The geometry and material files are converted from ABAQUS into Tahoe format.

SAMPLE APPLICATION

Several models were created using ProEngineer and ABAQUS CAE. Boundary conditions were applied in ABAQUS, and then the model was imported into IVDA. To test and verify the performance and capabilities of IVDA, several assembly test cases were created. In this paper, two of these test cases are presented to demonstrate the validity of using this program for product design. The "small-scale" assembly was represented by curved surfaces and a "large-scale" assembly was represented with a "real" engineering case.

To test a "small-scale" assembly, a pin on a base block was created. First, both models are loaded into IVDA using the menu. By scrolling through "Select Next Model", the user can select which part to move or modify. Collision detection was then turned on. The user could slide the pin into the base using the wand or the haptic device by selecting the pin in the menu. Collision detection allowed the user to assemble the parts with ease. Because the pin was the part of interest, an initial analysis of the part was performed. The stress contours were superimposed on the physical model. The user then returned to the Bounding Volume sub-menu and selects "Create new Bounding Volume". The user pointed the wand on the part. The bounding volume was completed when the user had selected two points using the wand. More points can be added to the bounding volume. Figure 6 shows a flowchart of the program's operation.

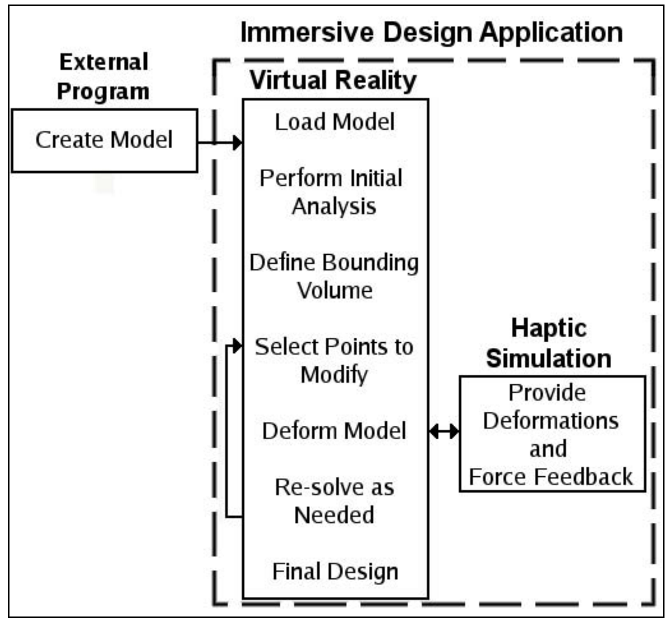

Figure 6: Flowchart for IVDA.

Once these steps were completed, the stress sensitivities were computed using a finite difference method. The user could deform the model by selecting the desired control points with the wand. Deformations are allowed in the x, y and z direction. The new stresses were computed using a Taylor series approximation, which can be inaccurate for large deformations. Therefore, the user had the option of using the PCG method to solve the systems of equations for more accurate stresses in IVDA.

Figure 7 shows the rectangular pin and base assembly (A) and corresponding Von Mises stress on the pin during the assembly process (B). Here, the pin was modeled with a radius of 0.9 in increments of 0.01 (Figure 7). The base was modeled with a hole radius of 1. Collision was enabled while the model was positioned. Steel material properties were applied to the pin and base. A corresponding Von Mises Stress of 1392.47 psi was calculated with a bending force applied on the pin. Figure 7-B shows that the pin has the highest Von Mises stress where the bending force is applied. Therefore, the bounding volume was placed in the region of highest stress. The pin was left inside of the base during shape change. When placing the bounding volume on the pin, the volume may intersect with the base, but bounding by collision detection will limit the engineer in the types of deformations allowed.

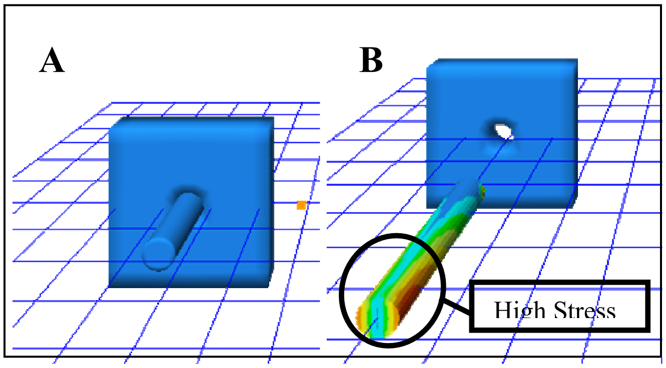

Figure 7: A: pin and base assembly, B: base assembly with Von Mises Stress in IVDA.

Figure 8 shows the pin with reduced Von Mises stress. The shape was changed by selecting the control points on the left side. The engineer selects the control points of interest with the wand and the selected points turn red. Unselected control points are blue in color. The user was able to reduce the stress on the pin while still maintaining the assembility of the parts. When the deformed shape intersected with the base part, collision detection prevented the user from deforming the model further. The deformed pin in Figure 8 is able to slide into the base until the deformation becomes too large and the two models intersect.

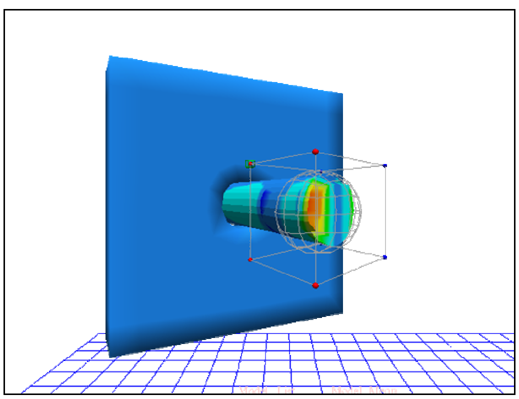

Figure 8: Pin and base assembly with reduced Von Mises Stress.

Some limitations of IVDA occurred with this assembly. More specifically, models with force, or press and locational fits would not be able to be assembled. However, running or sliding fits with certain assembly tolerances are ideal for IVDA. Nevertheless, limitations exist. A hole and shaft assembly may become problematic if the shaft diameter is exactly the base hole diameter. 5% clearance usually works depending on "mesh" size for rectangular models. Coarser "meshes" require increased tolerances.

Cylindrical shafts are much more complicated to assemble due to their curved surfaces. Hence, the number of nodes on the perimeter was designed to be constant at 16 nodes throughout several pin diameters. A 10% clearance must be observed for circular parts. Although OPCODE may not be highly accurate collision detection, especially for highly curved surfaces, it was chosen because of its ability to handle deforming meshes and it is computationally fast compared to other programs. In some cases, it is easier to perform the shape changes with the parts "exploded". Testing for assembility can occur at any time.

For the "large-scale" example, suspension assembly was modeled. The design of the individual parts was left intentionally crude to allow the engineer play with the models. The suspension assembly consists of a control arm, shock absorber, ball joint link and a brake disk. Rounds and other typical engineering features were left out, thus increasing stress sensitivities. Virtual assembly evaluation is required for "large-scale" assemblies when determining optimal designs. The control arm can be modified in several areas; especially the thickness can be reduced to minimize weight. In addition, adding or removing material from the swept features is an option. In this example, material was added to the model to reduce the stresses in the arm without affecting the second part.

The user is able to read the models and to perform initial assembly tasks. In addition, collision can be turned on or off, depending if the user wants "faster" assembly times. However, this option may not be used when parts are inserted into a second part, as the user may not notice overlapping or colliding parts. The designer can now place the parts and perform an individual stress analysis. Figure 9 shows the control arm with corresponding Von Mises stresses. A bounding volume can now be placed on the arm to allow shape changes.

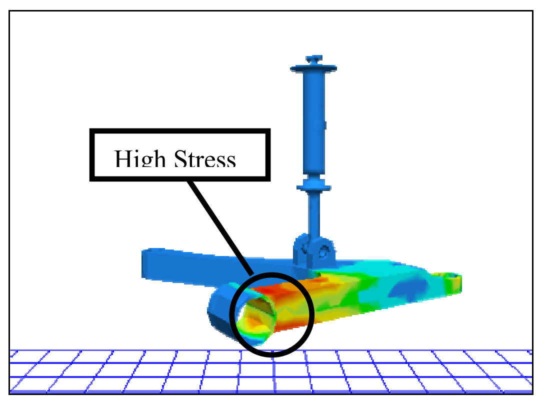

Figure 9: Suspension assembly in the IVDA with stresses.

Figure 9 shows the user assembling the deformed control arm. Real-time stress updates inform the engineer of stress intensities. The assembility of the parts can be tested while increasing the performance of parts. While deforming one model, the engineer can view the entire assembly and see how the shape changes change the overall assembled product. Deformations become extremely important during assembly. Using the nodal displacements calculated by Tahoe, the IVDA user can choose whether to display displacements.

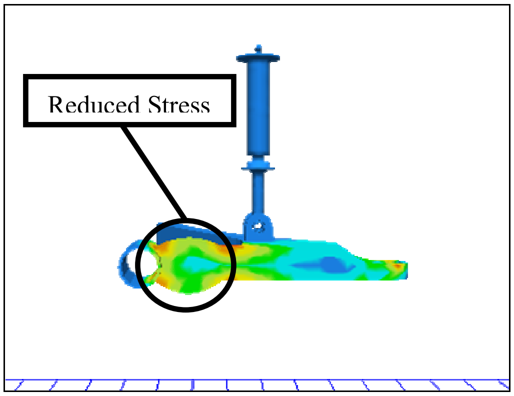

Figure 10: New geometry of control arm while assembled with suspension.

The shape change did not have any effect on the ease of assembly of the two parts. The stresses of the control arm were successfully reduced. The part can now undergo further design changes with new bounding volumes or the geometry can now be exported for reanalysis in ABAQUS. Due to the PCG approximation, a reanalysis of the new geometry is required. The process for large scale is similar to small scale, but greater complexity requires greater care to ensure that interference does not happen. Sometimes additional steps like simplifying the CAD model or deforming the parts in steps are needed to produce acceptable results with large scale models.

CONCLUSION

Besides combining finite element analysis with interactive VR and haptics, this application is unique in its ability to allow a designer to modify part shape while examining stress changes and then immediately proceed to checking assembly clearances. Current virtual assembly applications assume that the part geometry is fixed. With IVDA, the user can change the part geometry, examine stresses and check for ease of assembly with other parts all in an interactive immersive virtual environment. IVDA allows engineers to, work together on fast interactive investigations of multiple part shapes early in the product design process. More design options can be explored with IVDA when the analysis results are displayed in real-time, while displaying results accurately [22].

FUTURE WORK

The goal of this work is to develop a methodology that couples analysis with product design early in the product design cycle. Future work will involve refinement of the bounding volume creation and manipulation as well as improvements to the interactive analysis and haptic feedback force modeling

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DISCLOSURE

The opinions expressed here are the authors and do not represent endorsement by the National Science Foundation.

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