A half-century after the revolution, what should we teach current undergraduate geoscientists about lithospheric motion?

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Plate tectonics is a synthesis that combines a host of geological and geophysical data by means of a kinematic model of the motion of lithospheric plates. This symposium honors the major events of half a century past that led to the broad acceptance of plate tectonics as a better context for understanding global change over most of Earth's history. Since that first generation of plate-tectonic ideas, significant advances have accumulated in the diversity, quality, and volume of relevant data, in parallel with significant advances in the availability and power of computer resources at all levels of science and education. As more information has been gathered, details of the motions of Earth's lithosphere and associated geological consequences have continued to become ever more interesting and useful.

The typical undergraduate geoscience students of today were not alive during the birth of modern plate tectonics in the 1960s and early 1970s, and neither were many of their parents. Our collective impression (based on decades of teaching courses in tectonics, structural geology, physical geology, and mathematics) is that current students enjoy hearing stories about the geological consequences of "the motion of plates," but lack the knowledge or skills needed to develop virtually any quantitative description of lithospheric motion. Their understanding is largely based on qualitative descriptions of first-generation ideas of plate tectonics offered in introductory textbooks or literature syntheses. The capacity to glean useful quantitative information about lithospheric motions from GNSS data and other relevant kinematic observations is a fundamental ability for modern geoscientists to develop, requiring a functional knowledge of certain basic mathematical techniques and computer skills.

How should geoscience educators facilitate student learning so that members of the next generation of geoscientists are able to advance our understanding of lithospheric dynamics and kinematics? First, we must embrace our responsibility to help our students develop quantitative skills rather than limit ourselves to telling qualitative stories. Just as plate tectonics provides a useful context for understanding global change, it can also provide a useful focus for undergraduate geoscientists to learn about mathematics, statistics, and computer coding -- fundamental skills that will be useful throughout their careers. As a group of hopeful idealists with expertise in lithospheric kinematics, geoscience education, and quantitative methods, we intend to develop curricular resources during the next few years that will help guide undergraduate geoscience students to a practical working knowledge of lithospheric kinematics.

B. Some Design Assumptions

1. The student wants to master the material presented.
2. The student's math skills are that of a typical US-high-school graduate, and are probably rusty.
3. The student has little or no functional knowledge of computer coding.
4. The student has little or no functional knowledge of quantitative lithospheric kinematics.
5. What information a student has about plate kinematics is likely full of misconceptions.

C. Some Design Fundamentals

1. Teach about current understanding using current data.
2. Scaffold mathematical ideas and skills as needed.
3. Build useful knowledge to solve authentic (but basic) problems.
4. Incorporate uncertainties throughout.
5. Fully credit the originators of fundamental insights, but leave the recitation of history to science historians.

D. The spectrum of lithospheric motion and related major geologic effects in the present and near-present

We begin the process by having students gain basic knowledge of Earth as it is today and through the recent past through maps providing earthquake information (locations, depths, focal mechanisms), locations of active volcanoes, maps of active faults, relevant bathymetric features of the world's oceans (ridges, axial rifts, transform faults, oceanic fracture zones, trenches), and relevant topographic features of the continents (active mountains and rifts). Then we explore Earth's lithospheric motions as they are observed in the present [e.g., from GNSS data] and near-present (e.g., from instantaneous models of global plate motion, such as Morvel-56 of Demets and others [2010]). The idea is for students to access relevant empirical data and place it in a global geographic context.

E. Some mathematical ideas we need to help students develop in order to solve basic problems in lithospheric kinematics

1. least-square and other spatial statistics
2. coordinate systems (reference frames)
3. 3-space vectors and associated uncertainties
4. location vectors
5. vectors as matrices
6. vector and matrix operations (matrix arithmetic, cross product, dot product, etc.)
7. coordinate transformations
8. rotation matrices
9. tangential velocity vectors and uncertainties
10. angular velocity vectors and uncertainties
11. instantaneous velocity vectors and finite-motion paths

F. Computer coding to provide computational assistance while working with problems in lithospheric kinematics

We consider plate kinematics to be an attractive opportunity to help students begin to learn how to write functional computer code to solve practical problems. Rather than fuss over which computer language we should focus on, we have decided to create opportunities for students to learn how to write code in one (or more) of several languages. We will develop coding examples and exercises that parallel and compliment the analytical solutions to kinematic problems, using a spreadsheet, *MatLab*, *Mathematica*, and *Python.* This provides a student with the opportunity to gain an initial familiarity with several of the languages used in geoscience applications and research.

G. Reference frames used in geodesy and lithospheric kinematics

We will introduce the primary types of reference frame used in lithospheric kinematics, for example, no-net rotation solutions, ITRF, various hot-spot solutions, and fixed-plate solutions. This will include a familiarization with current published implementations of reference frame solutions.

H. Sources of infinitesimal/instantaneous displacement/velocity data

We will examine several types of empirical data currently used to measure the motion of points or areas of the lithosphere. In each case, a basic description of the phenomenon that is measured will be followed by information about how to obtain current data. Sources include GNSS measurements, offset marine magnetic anomalies, fault offsets, and distance-age relationships along hot-spot tracks. Students will also learn how to obtain current infinitesimal/instantaneous displacement/velocity data.

I. Interpreting infinitesimal/instantaneous displacement/velocity data in an area of interest

We will facilitate student exploration of the empirical record of lithospheric motion in an area. Students will learn how to use GNSS data from three non-colinear stations to measure crustal strain between the stations, building a map of regional strain from a network of GNSS stations. They will work to understand significant velocity discontinuities, developing understanding of lithospheric deformation along and across plate boundaries.

J. Finite motion — reconstructing the past and modeling from the past to the future

Stage poles, aspects of the sigmoid shape of oceanic fracture zones, paleomagnetic pole data, and displaced unique petrologic/paleontologic assemblages will be introduced as empirical constraints for finite-motion studies. We will introduce the cycloid model for modeling finite displacements of a few million years to a few tens of millions of years, and help students learn to model how plate motion might affect specific plate boundaries ± ~10 Myr.

K. Misconceptions

In light of material developed above, a variety of common misconceptions will be brought to light, and then they will be consigned to the dustbin of history.

References and other information are at http://CroninProjects.org/Tectonics-Paris/