CLAIMS

1. A computer system configured to train a neural network to extract one or more mechanical properties of a material from indentation parameters for the material, the computer system comprising:

at least one computer processor; and

at least one non-transitory computer readable medium encoded with instructions that, when executed by the at least one computer processor, perform a method, comprising:

providing as input to the neural network, the indentation parameters for the material;

training the neural network to map the input indentation parameters to the one or more mechanical properties of the material; and

storing the trained neural network on the at least one non-transitory computer readable medium~~.~~

~~2. The computer system of claim 1~~, wherein the neural network includes a first portion configured to receive as input low-fidelity indentation parameters, a second portion configured to receive as input high-fidelity indentation parameters, and an integration portion that integrates one or more outputs of the first portion and one or more outputs of the second portion.

2~~3~~. The computer system of claim 1~~2~~, wherein training the neural network comprises training the first portion of the neural network based on the low-fidelity indentation parameters and training the second portion of the neural network based on the high-fidelity indentation parameters.

3~~4~~. The computer system of claim 2~~3~~, wherein training the neural network further comprises integrating both the high-fidelity indentation parameters and the low-fidelity implementation parameters using convolution and/or recursion.

45. The computer system of claim 23, wherein a number of datum in the high-fidelity indentation parameters used to train the first portion of the neural network is less than a number of datum in the low-fidelity indentation parameters used to train the second portion of the neural network.

56. The computer system of claim 12, wherein the high-fidelity indentation parameters include first indentation parameters determined from one or more simulations and second indentation parameters determined from one or more indentation tests on the material.

67. The computer system of claim 12, wherein training the neural network comprises training the neural network to reduce at least one systematic error by using data determined from one or more indentation tests on the material to determine at least some of the high-fidelity indentation parameters.

78. The computer system of claim 12, wherein the low-fidelity indentation parameters include indentation parameters determined using one or more simulations.

89. The computer system of claim 12, wherein

the first portion and/or the second portion of the neural network are pre-trained using a baseline training process; and

training the neural network to map the input indentation parameters to the one or more mechanical properties of the material comprises training only the second portion of the neural network with high-fidelity indentation parameters.

910. The computer system of claim 1, wherein the neural network includes convolutional and recursive linear and/or nonlinear integration of training data with at least three levels of fidelities.

101. The computer system of claim 1, wherein the indentation parameters include indentation parameters for multiple indenter geometries.

112. The computer system of claim 101, wherein the multiple indenter geometries have different half-included tip angles.

123. The computer system of claim 101, wherein the multiple indenter geometries include multiple indenter shapes.

134. The computer system of claim 1, wherein the one or more mechanical properties include a reduced Young's modulus, a yield strength, and/or a strain hardening parameter.

145. The computer system of claim 134, wherein the one or more mechanical properties include at least two of a reduced Young's modulus, a yield strength, and a strain hardening parameters.

156. The computer system of claim 1, wherein the one or more mechanical properties include a plurality of points on a stress-strain curve.

167. The computer system of claim 156, wherein the one or more mechanical properties include a plurality of strain values at different plastic strains.

178. The computer system of claim 1, wherein the one or more indentation parameters include one or more indentation parameters extracted from a loading portion of an indentation curve, an unloading portion of the indentation curve, and/or both the loading and the unloading portion of the indentation curve.

189. The computer system of claim 1, wherein the one or more indentation parameters include one or more of loading curvature, initial unloading slope, and plastic work ratio.

1920. The computer system of claim 189, wherein the one or more indentation parameters include the loading curvature, the initial unloading slope and the plastic work ratio.

201. The computer system of claim 1, wherein the method further comprises:

receiving load-displacement data for the material; and

determining the one or more indentation parameters from the received load-displacement data.

212. The computer system of claim 1, wherein the material comprises a 3D printed material.

223. The computer system of claim 1, wherein training the neural network comprises training the neural network using training data having more than two levels of fidelities.

234. The computer system of claim 1, wherein the neural network includes:

N portions wherein N is greater than two, each of the N portions being configured to receive as input indentation parameters having a different fidelity, and

at least one integration portion configured to integrate one or more outputs of the N portions.

245. The computer system of claim 234, wherein training the neural network comprises training the N portions of the neural network based on indentation parameters having respective fidelities.

~~26. A computer system configured to extract one or more mechanical properties for a material based on one or more indentation parameters for the material, the system comprising:~~

~~at least one computer processor; and~~

at least one non-transitory computer readable medium encoded with instructions that, when executed by the at least one computer processor, perform a method, comprising:

receiving load-displacement data from one or more instrumented indentation tests on the material;

determining the indentation parameters for the material based, at least in part, on the received load-displacement data;

providing as input to a trained neural network, the indentation parameters for the material;

determining, based on an output of the trained neural network, the one or more mechanical properties of the material; and

displaying an indication of the determined one or more mechanical properties of the material to a user of the computer system.

27. The computer system of claim 26, wherein the trained neural network was trained using high-fidelity indentation parameters and low-fidelity indentation parameters.

28. The computer system of claim 26, wherein the received load-displacement data comprises load-displacement data from instrumented indentation tests having different indenter geometries.

29. The computer system of claim 28, wherein the different indenter geometries have different half-included tip angles.

30. The computer system of claim 29, wherein the different indenter geometries include different indenter shapes.

31. The computer system of claim 26, wherein the one or more mechanical properties include a reduced Young's modulus, a yield strength, and/or a strain hardening parameter.

~~32. The computer system of claim 31, wherein the one or more mechanical properties include two or more of a reduced Young's modulus, a yield strength, and a strain hardening parameter.~~

~~33. The computer system of claim 26, wherein the one or more mechanical properties include a plurality of points on a stress-strain curve.~~

~~34. The computer system of claim 33, wherein the one or more mechanical properties include a plurality of strain values at different plastic strains.~~

~~35. The computer system of claim 26, wherein the one or more indentation parameters include one or more indentation parameters extracted from a loading portion of an indentation curve, an unloading portion of the indentation curve, and/or both the loading portion and the unloading portion of the indentation curve.~~

~~36. The computer system of claim 26, wherein the one or more indentation parameters include one or more of loading curvature, initial unloading slope, and plastic work ratio.~~

~~37. The computer system of claim 26, wherein the material comprises a 3D printed material.~~

~~38. The computer system of claim 26, further comprising:~~

~~an instrumented indentation system configured to perform at least one of the one or more instrumented indentation tests on the material to generate the load-displacement data.~~

~~39. The computer system of claim 38, wherein the instrumented indentation system comprises a robotic arm.~~

~~40. The computer system of claim 26, wherein the received load-displacement data comprises one or more load-displacement curves, and wherein the indentation parameters comprise values derived from the one or more load-displacement curves.~~

25~~41~~. A method of training a neural network to extract one or more mechanical properties of a material from indentation parameters for the material, the method comprising:

providing as input to the neural network, the indentation parameters for the material;

training, using at least one computer processor, the neural network to map the input indentation parameters to the one or more mechanical properties of the material; and

storing the trained neural network on at least one non-transitory computer readable medium~~.~~

~~42. The method of claim 41~~, wherein the neural network includes a first portion configured to receive as input low-fidelity indentation parameters, a second portion configured to receive as input high-fidelity indentation parameters, and an integration portion that integrates one or more outputs of the first portion and one or more outputs of the second portion.

26~~43~~. The method of claim 25~~42~~, wherein training the neural network comprises training the first portion of the neural network based on the low-fidelity indentation parameters and training the second portion of the neural network based on the high-fidelity indentation parameters.

27~~44~~. The method of claim 26~~43~~, wherein training the neural network further comprises integrating both the high-fidelity indentation parameters and the low-fidelity implementation parameters using convolution and/or recursion.

2845. The method of claim 2643, wherein a number of datum in the high-fidelity indentation parameters used to train the first portion of the neural network is less than a number of datum in the low-fidelity indentation parameters used to train the second portion of the neural network.

2946. The method of claim 2542, wherein the high-fidelity indentation parameters include first indentation parameters determined from one or more simulations and second indentation parameters determined from one or more indentation tests on the material.

3047. The method of claim 2542, wherein training the neural network comprises training the neural network to reduce at least one systematic error by using data determined from one or more indentation tests on the material to determine at least some of the high-fidelity indentation parameters.

3148. The method of claim 2542, wherein the low-fidelity indentation parameters include indentation parameters determined using one or more simulations.

3249. The method of claim 2542, wherein

the first portion and/or the second portion of the neural network are pre-trained using a baseline training process, and

training the neural network to map the input indentation parameters to the one or more mechanical properties of the material comprises training only the second portion of the neural network with high-fidelity indentation parameters.

3350. The method of claim 2541, wherein the neural network includes convolutional and recursive linear and/or nonlinear integration of training data with at least three levels of fidelities.

3451. The method of claim 2541, wherein the indentation parameters include indentation parameters for multiple indenter geometries.

3552. The method of claim 3451, wherein the multiple indenter geometries have different half-included tip angles.

3653. The method of claim 3451, wherein the multiple indenter geometries include multiple indenter shapes.

3754. The method of claim 2541, wherein the one or more mechanical properties include a reduced Young's modulus, a yield strength, and/or a strain hardening parameter.

3855. The method of claim 3754, wherein the one or more mechanical properties include at least two of a reduced Young's modulus, a yield strength, and a strain hardening parameters.

3956. The method of claim 2541, wherein the one or more mechanical properties include a plurality of points on a stress-strain curve.

4057. The method of claim 3956, wherein the one or more mechanical properties include a plurality of strain values at different plastic strains.

4158. The method of claim 2541, further comprising:

extracting the one or more indentation parameters from a loading portion of an indentation curve, an unloading portion of the indentation curve, and/or both the loading and the unloading portion of the indentation curve.

4259. The method of claim 2541, wherein the one or more indentation parameters include one or more of loading curvature, initial unloading slope, and plastic work ratio.

4360. The method of claim 4259, wherein the one or more indentation parameters include the loading curvature, the initial unloading slope and the plastic work ratio.

4461. The method of claim 2541, further comprising:

receiving load-displacement data for the material; and

determining the one or more indentation parameters from the received load-displacement data.

4562. The method of claim 2541, wherein the material comprises a 3D printed material.

4663. The method of claim 2541, wherein training the neural network comprises training the neural network using training data having more than two levels of fidelities.

4764. The method of claim 2541, wherein the neural network includes:

N portions wherein N is greater than two, each of the N portions being configured to receive as input indentation parameters having a different fidelity, and

at least one integration portion configured to integrate one or more outputs of the N portions.

4865. The method of claim 4764, wherein training the neural network comprises training the N portions of the neural network based on indentation parameters having respective fidelities.

~~66. A method of extracting one or more mechanical properties for a material based on one or more indentation parameters for the material, the method comprising:~~

~~receiving load-displacement data from one or more instrumented indentation tests on the material;~~

~~determining, by at least one computer processor, the indentation parameters for the material based, at least in part, on the received load-displacement data;~~

~~providing as input to a trained neural network, the indentation parameters for the material;~~

~~determining, based on an output of the trained neural network, the one or more mechanical properties of the material; and~~

displaying an indication of the determined one or more mechanical properties of the material to a user of the computer system.

67. The method of claim 66, wherein the trained neural network was trained using high-fidelity indentation parameters and low-fidelity indentation parameters.

68. The method of claim 66, wherein the received load-displacement data comprises load-displacement data from instrumented indentation tests having different indenter geometries.

69. The method of claim 68, wherein the different indenter geometries have different half-included tip angles.

70. The method of claim 68, wherein the different indenter geometries include different indenter shapes.

71. The method of claim 66, wherein the one or more mechanical properties include a reduced Young's modulus, a yield strength, and/or a strain hardening parameter.

72. The method of claim 71, wherein the one or more mechanical properties include two or more of a reduced Young's modulus, a yield strength, and a strain hardening parameter.

73. The method of claim 66, wherein the one or more mechanical properties include a plurality of points on a stress-strain curve.

74. The method of claim 73, wherein the one or more mechanical properties include a plurality of strain values at different plastic strains.

75. The method of claim 66, further comprising:

extracting the one or more indentation parameters from a loading portion of an indentation curve, an unloading portion of the indentation curve, and/or both the loading portion and the unloading portion of the indentation curve.

76. The method of claim 66, wherein the one or more indentation parameters include one or more of loading curvature, initial unloading slope, and plastic work ratio.

77. The method of claim 66, wherein the material comprises a 3D printed material.

78. The method of claim 66, further comprising:

using an instrumented indentation system to perform at least one of the one or more instrumented indentation tests on the material to generate the load-displacement data.

79. The method of claim 78, wherein the instrumented indentation system comprises a robotic arm.

80. The method of claim 66, wherein the received load-displacement data comprises one or more load-displacement curves, and wherein the indentation parameters comprise values derived from the one or more load-displacement curves.