

CyberMAGICS Workshop: Reactive Molecular Dynamics

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**Supported by National Science
Foundation, Award OAC-2118061**



CyberMAGICS Workshop, June 30, 2022

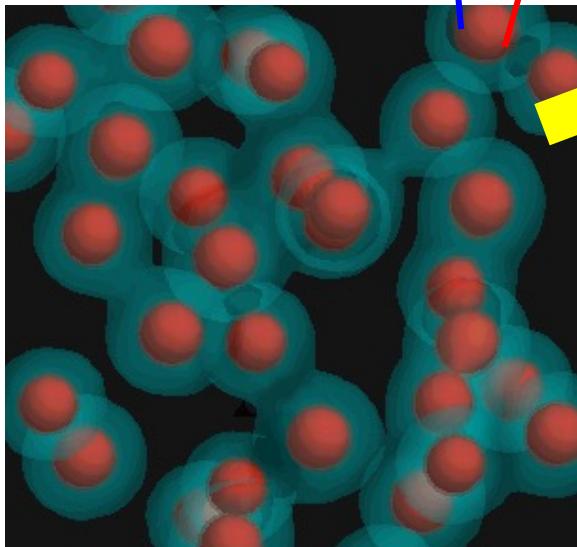


Hierarchy of Molecular Dynamics Methods

$$m_i \frac{d^2 \mathbf{r}_i}{dt^2} = -\frac{\partial}{\partial \mathbf{r}_i} E_{MD}(\{\mathbf{r}_i\})$$

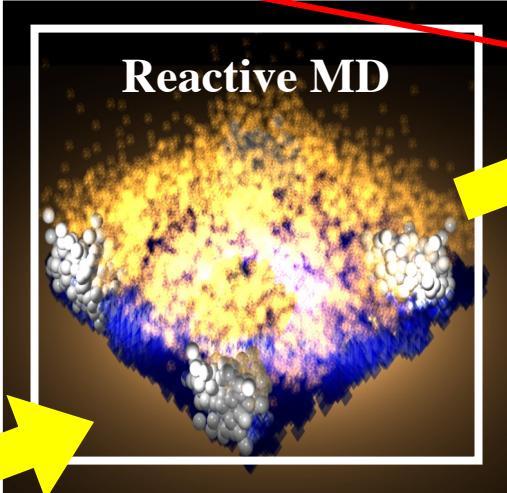
$$\min E_{QM}(\{\psi_n(\mathbf{r})\})$$

Electron wave function



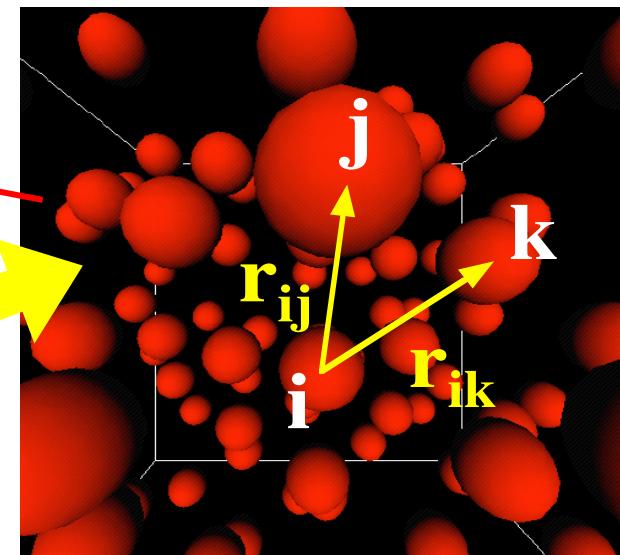
Quantum Mechanics (QM)

Atom

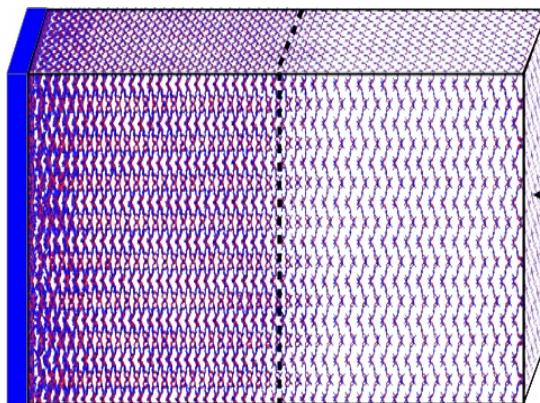


- MD with empirical interactions $\sim O(N)$
Long-time (10^9 steps) & large size (10^{12} atoms)
- DFT quantum MD $\sim O(N^3)$
Short-time (10^4 steps) & small size (~ 400 atoms)
- Divide-and-Conquer QMD $\sim O(N)$: Al/Li nanoparticle in water using **16K atoms** for **30,000** steps

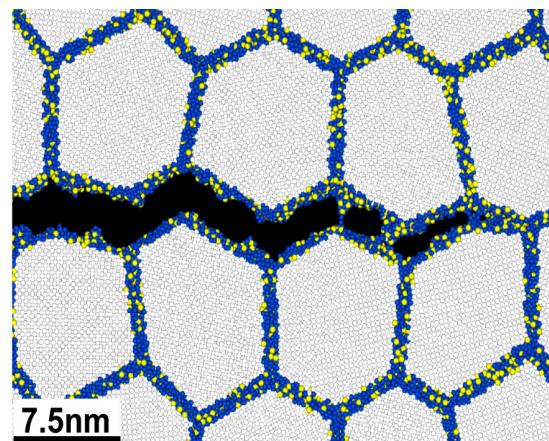
Molecular Dynamics (MD)



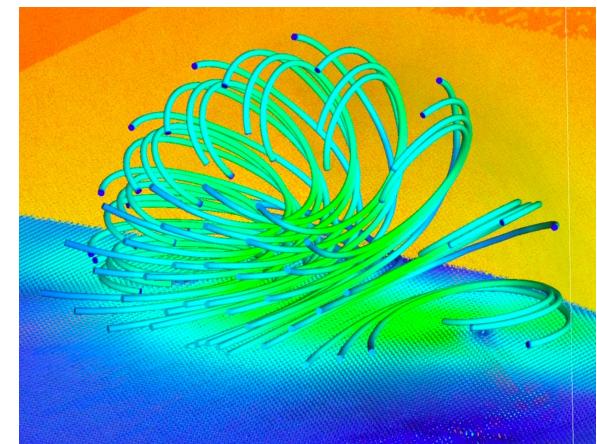
Large-Scale Reactive MD Simulations



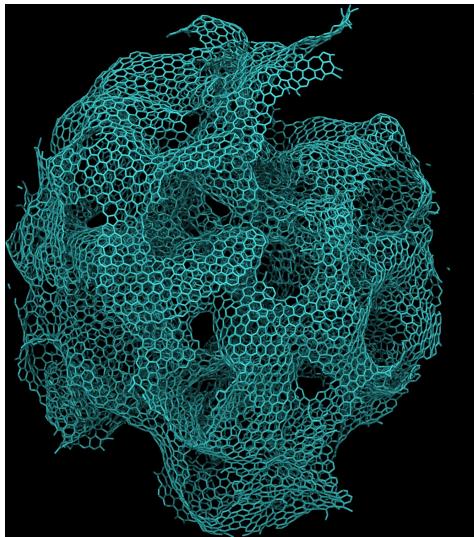
Shock-induced chemical reaction



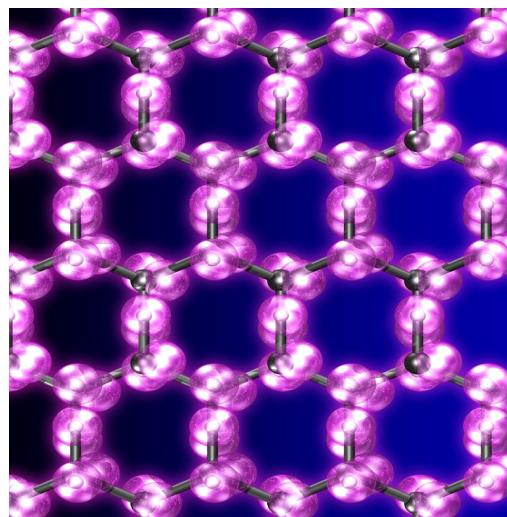
Stress corrosion cracking



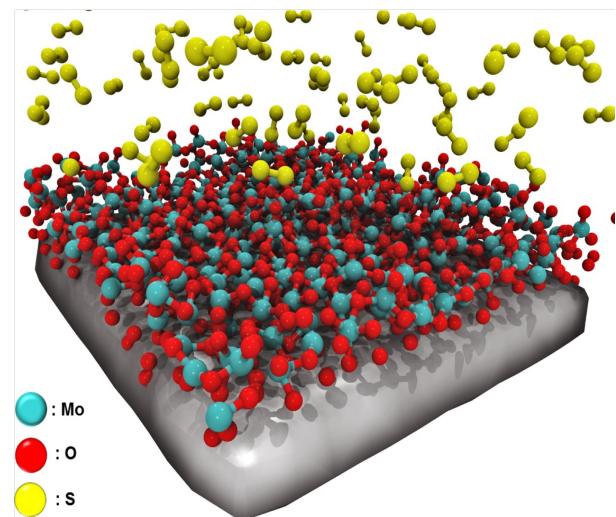
Underwater bubble collapse



Oxidation of nanoparticle



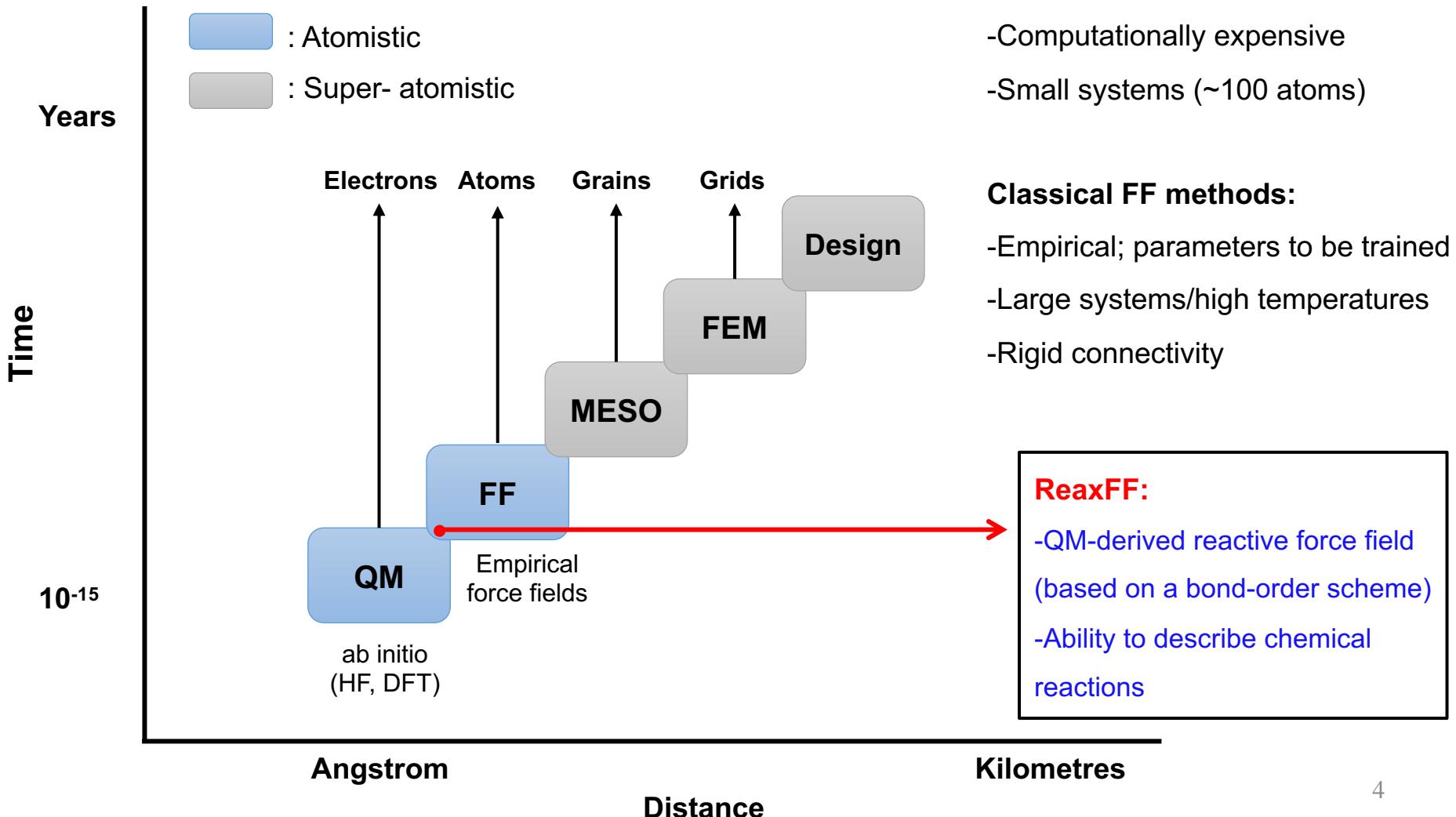
Dielectric polymers



2D material synthesis

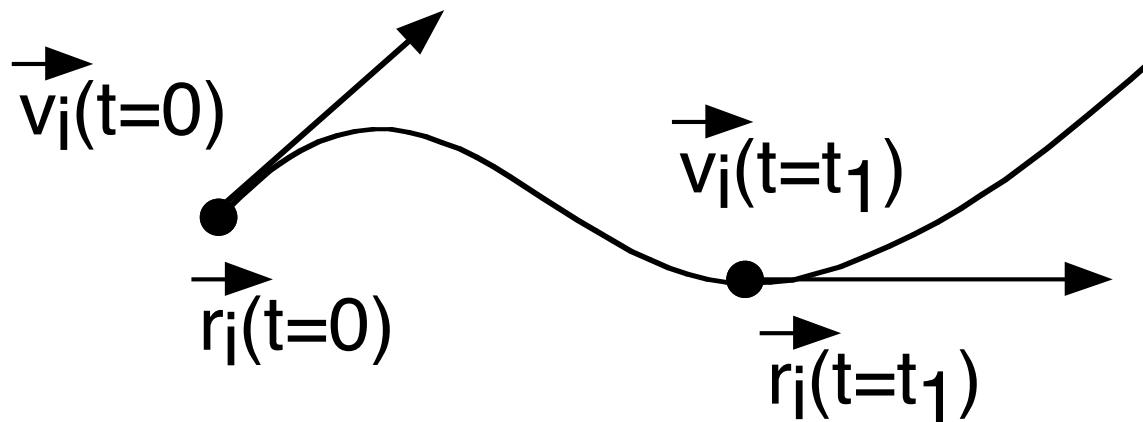
Basic Concepts of ReaxFF Forcefield

• Multi-scale Computational Modeling



Basic Concepts of ReaxFF Forcefield

- What is Molecular dynamics (MD) simulation?



Numerically solve Newton's
equation of motion

$$\vec{F}(t) = m \frac{d^2 \vec{r}_i}{dt^2} = - \frac{d}{d \vec{r}_i} V(\vec{r}_i \dots \vec{r}_N)$$

Interatomic potential; force field

Basic Concepts of ReaxFF Forcefield

- ReaxFF general energy terms*

$$E_{\text{system}} = E_{\text{bond}} + E_{\text{over}} + E_{\text{val}} + E_{\text{tors}} + E_{\text{vdWaals}} + E_{\text{Coulomb}}$$

The equation is shown with a blue bracket underneath grouping the first four terms (E_{bond}, E_{over}, E_{val}, E_{tors}) as 'Bonded interactions'. Another blue bracket groups the last two terms (E_{vdWaals}, E_{Coulomb}) as 'Non-bonded interactions'.

Bonded interactions

Non-bonded interactions

E_{bond}: Bond energy; two-body attractive term

E_{over}: Over-coordination energy; penalty for overcoordinating atoms

E_{val}: Angle strain energy; three-body term

E_{tors}: Torsion energy; four-body term

E_{vdWaals}: van der Waals interactions

E_{Coulomb}: Coulomb interactions

*van Duin, Adri CT, et al. *The Journal of Physical Chemistry A* **105** (2001): 9396-9409.

Basic Concepts of ReaxFF Forcefield

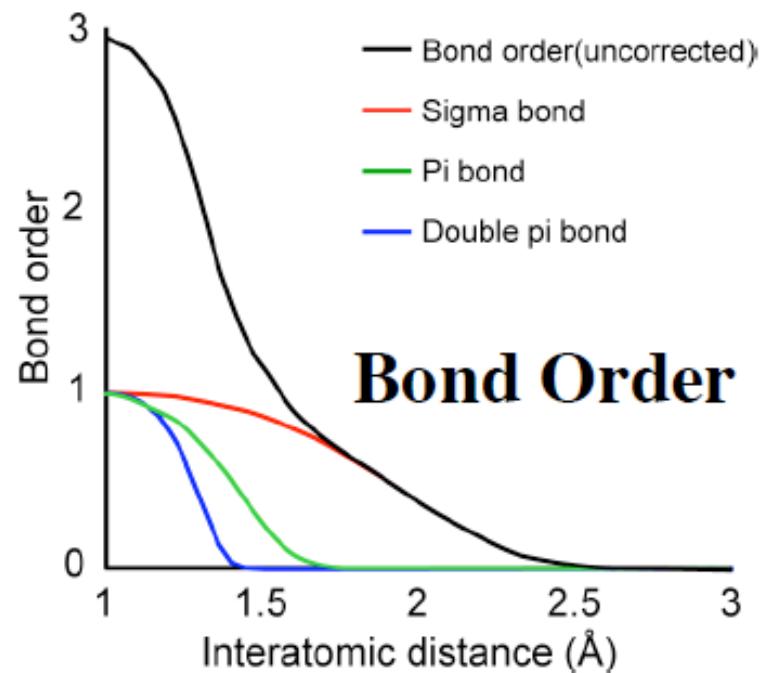
- Key features of ReaxFF – 1*

- A bond order is calculated and updated every step, thus allowing for chemical reactions during MD simulations.

A bond-order/distance relationship

$$BO_{ij} = \exp \left[p_{bo,1} \cdot \left(\frac{r_{ij}}{r_o^\sigma} \right)^{p_{bo,2}} \right] + \exp \left[p_{bo,3} \cdot \left(\frac{r_{ij}}{r_o^\pi} \right)^{p_{bo,4}} \right] + \exp \left[p_{bo,5} \cdot \left(\frac{r_{ij}}{r_o^{\pi\pi}} \right)^{p_{bo,6}} \right]$$

C-C bond order



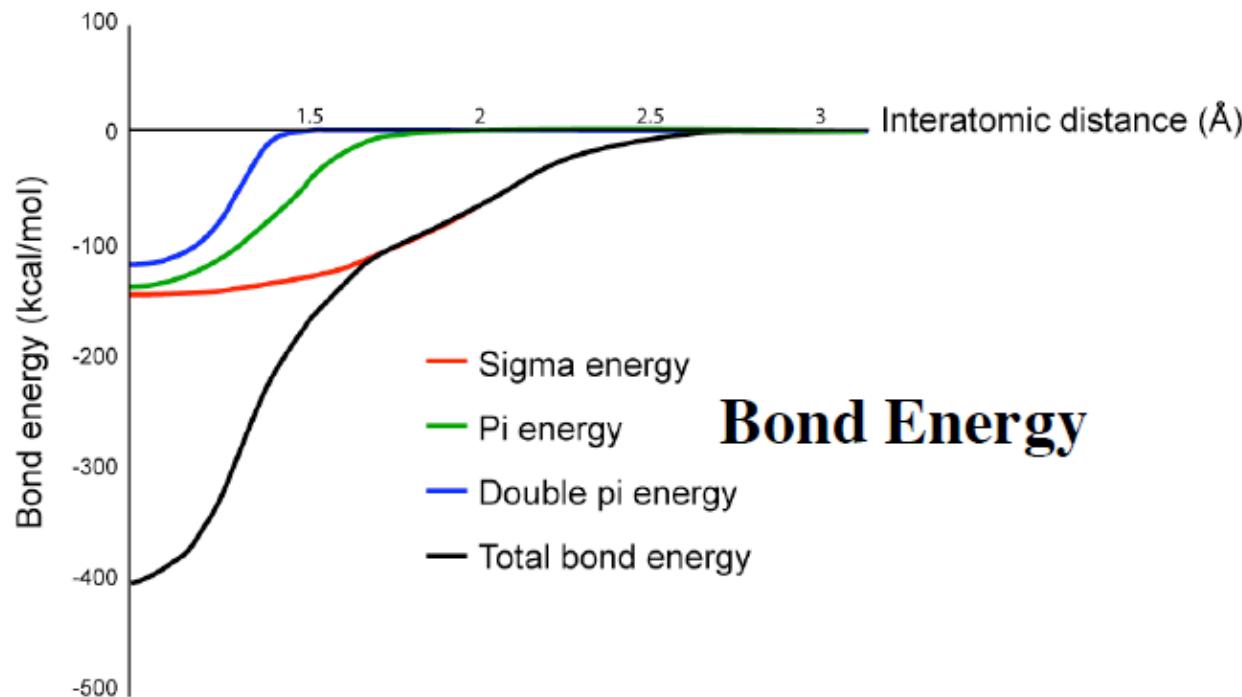
*Russo, Michael F., and Adri CT van Duin. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms* **269** (2011): 1549-1554.

Basic Concepts of ReaxFF Forcefield

- Key features of ReaxFF – 2*

- All bonded-interactions are made of bond-order dependent.

$$E_{bond} = -D_e^\sigma \cdot BO_{ij}^\sigma \cdot f(BO_{ij}^\sigma) - D_e^\pi \cdot BO_{ij}^\pi - D_e^{\pi\pi} \cdot BO_{ij}^{\pi\pi}$$



*Russo, Michael F., and van Duin, Adri. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms* **269** (2011): 1549-1554.

Basic Concepts of ReaxFF Forcefield

- Key features of ReaxFF – 3*

- Non-bonded interactions (van der Waals and Coulomb) are calculated between every atom pair. (*i.e.*, no exception)
- ReaxFF employs the QEq method,** a geometry-dependent point charge calculations scheme, to update point charges for the entire system.

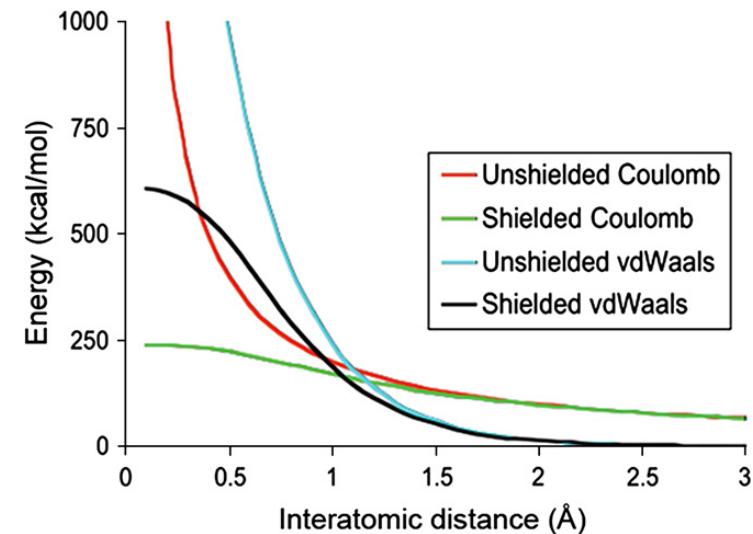
$$E_{vdWaals} = Tap \cdot D_{ij} \cdot \left\{ \exp \left[\alpha_{ij} \cdot \left(1 - \frac{f_{13}(r_{ij})}{r_{vdW}} \right) \right] - 2 \cdot \exp \left[\frac{1}{2} \cdot \alpha_{ij} \cdot \left(1 - \frac{f_{13}(r_{ij})}{r_{vdW}} \right) \right] \right\}$$

A shielded Morse potential

$$f_{13}(r_{ij}) = \left[r_{ij}^{p_{vdW1}} + \left(\frac{1}{\gamma_w} \right)^{p_{vdW1}} \right]^{\frac{1}{p_{vdW1}}}$$

$$E_{Coulomb} = C \cdot \frac{q_i \cdot q_j}{[r_{ij}^3 + (1/\gamma_{ij})^3]^{1/3}}$$

A shielded Coulomb potential



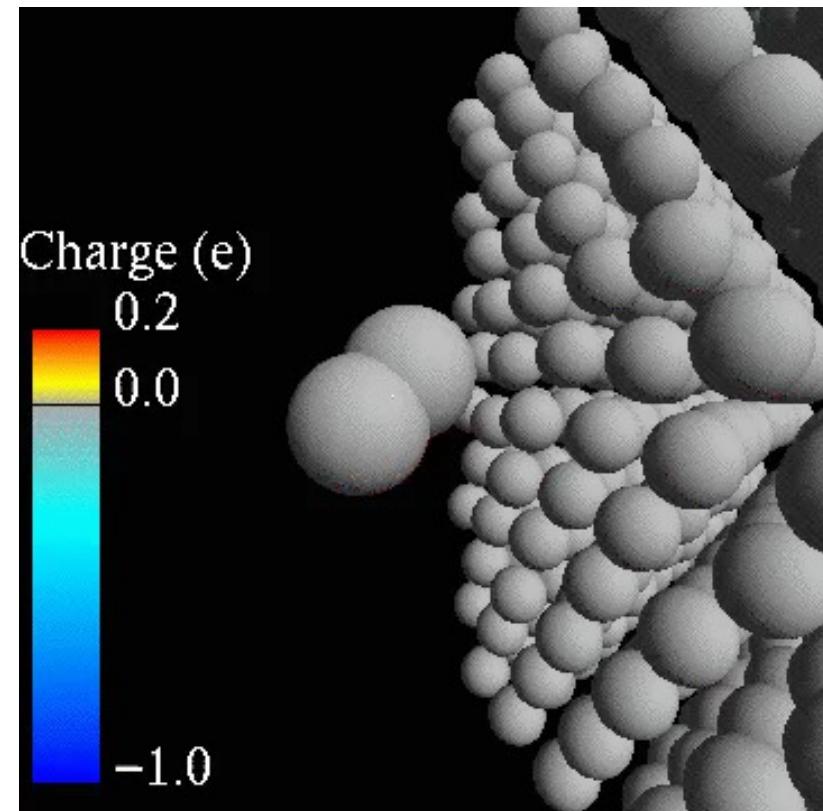
*Russo, Michael F., and Adri CT van Duin. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms* **269** (2011): 1549-1554.

Rappe, Anthony K., and William A. Goddard III. *The Journal of Physical Chemistry* **95 (1991): 3358-3363.

Basic Concepts of ReaxFF Forcefield

- Key features of ReaxFF – 4**
- Charge-equilibration (QE_q)
→ Charge transfer

Determine atomic charges
 $\{q_i \mid i = 1, \dots, N\}$ every MD step
to minimize $E_{\text{ES}}(\mathbf{r}^N, q^N)$ with
charge-neutrality constraint: $\sum_i q_i = 0$

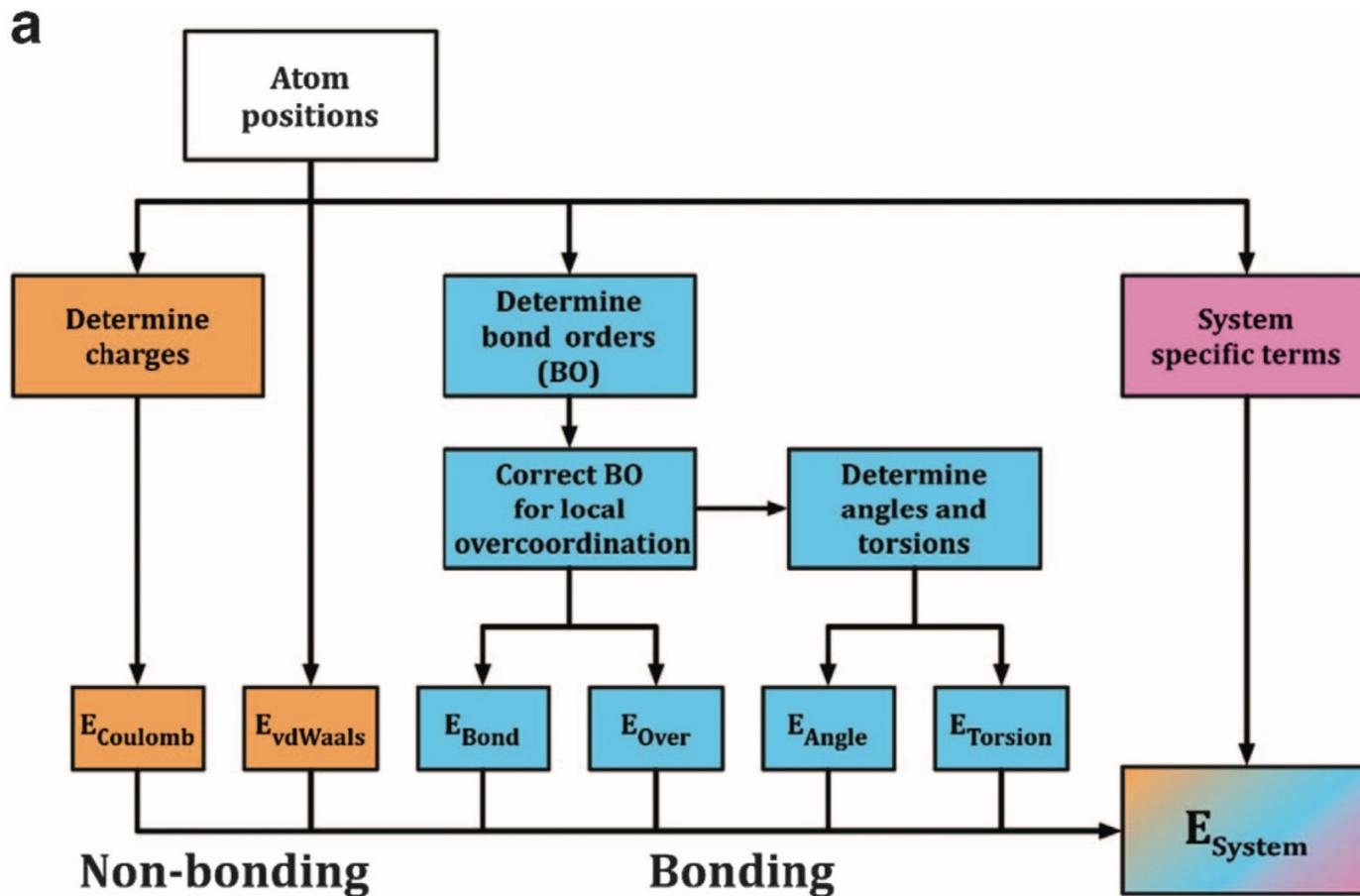


O₂ dissociation on Al(111)

$$E_{\text{ES}}(\mathbf{r}^N, q^N) = \sum_i \left(\chi_i q_i + \frac{1}{2} J_i q_i^2 \right) + \sum_{i < j} \int d\mathbf{x} \int d\mathbf{x}' \frac{\rho_i(q_i; \mathbf{x} - \mathbf{r}_i) \rho_j(q_j; \mathbf{x}' - \mathbf{r}_j)}{|\mathbf{x} - \mathbf{x}'|}$$

Basic Concepts of ReaxFF Forcefield

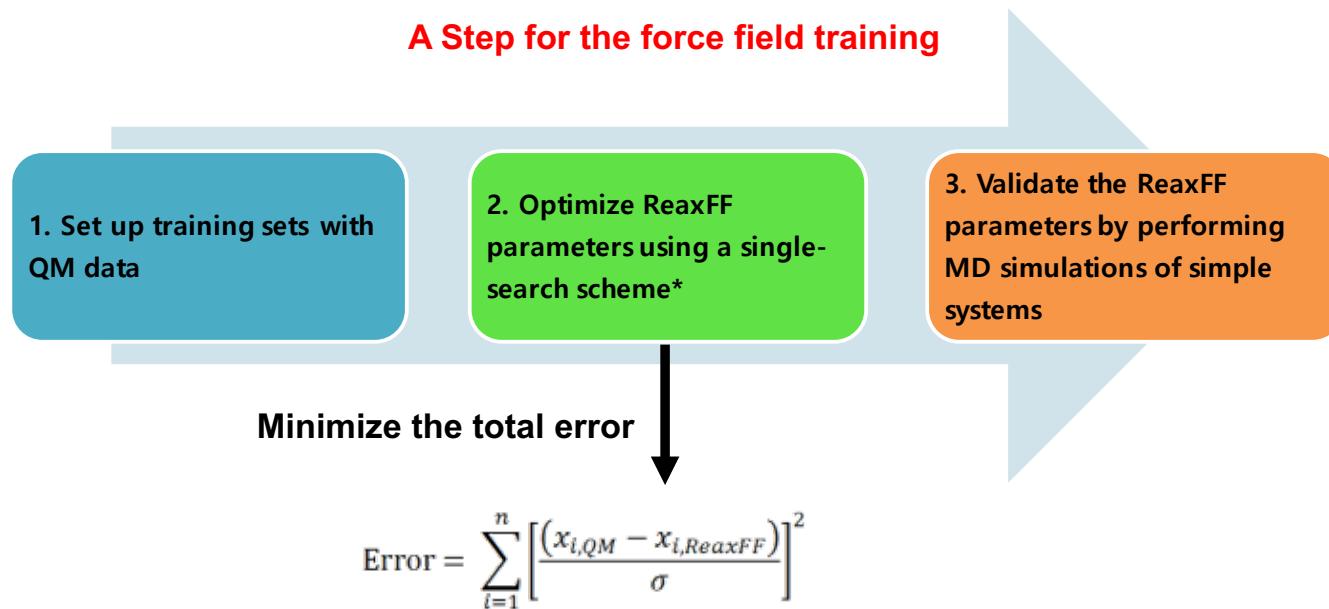
- ReaxFF flow diagram*



*Senftle, Thomas, et al. *npj Computational Materials* **2** (2016).

Basic Concepts of ReaxFF Forcefield

- How to get ReaxFF reactive force field parameters?
 - Do search Google Scholar:
<https://scholar.google.com/>
 - Develop your ReaxFF force field parameters (non-trivial)

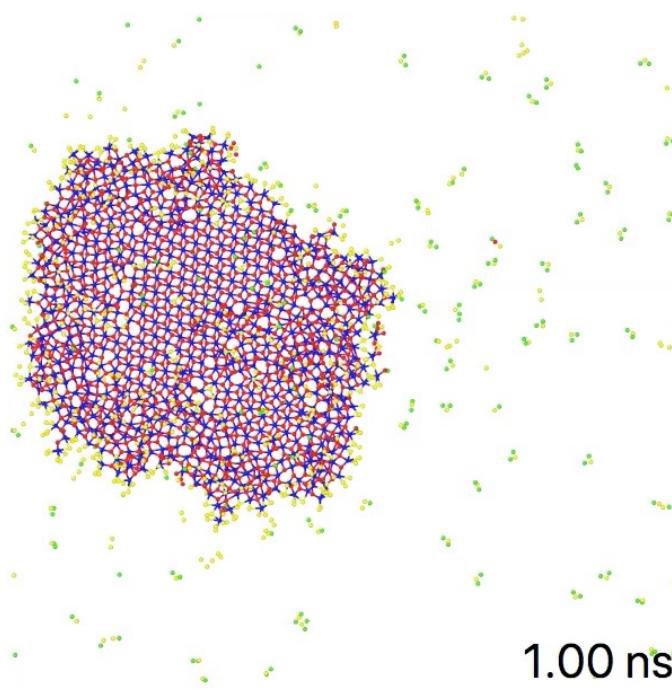


* van Duin, A. C. T.; Jan, M.; de Graaf, B. J. Chem. Soc., Faraday Trans. 1994, 90, (19), 2881-2895.

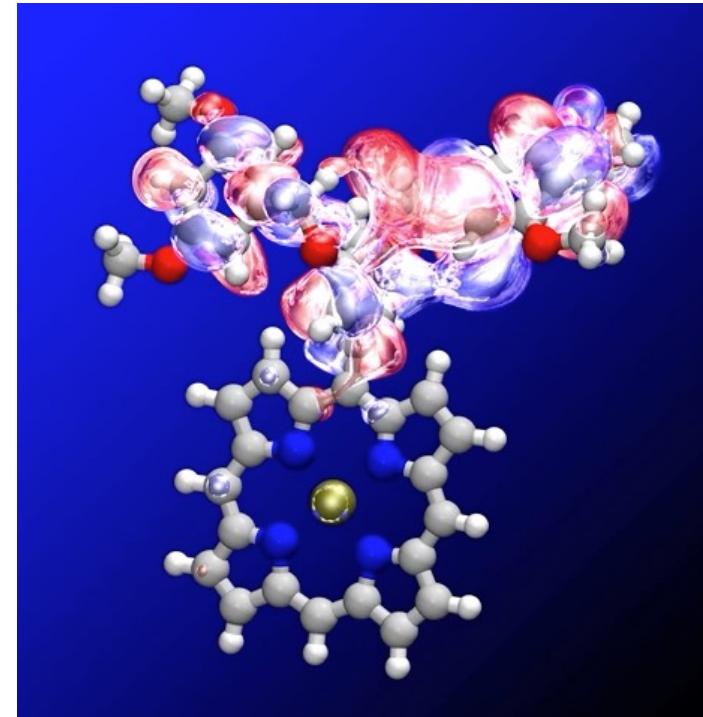
Reactive and Quantum MD Software

RXMD: Reactive molecular dynamics software for desktop to supercomputing platforms

QXMD: Quantum dynamics software with non-adiabatic extensions



Sulfidization of MoO_3 nanoflake



Electron transfer in light-harvesting molecule

Extended-Lagrangian Method

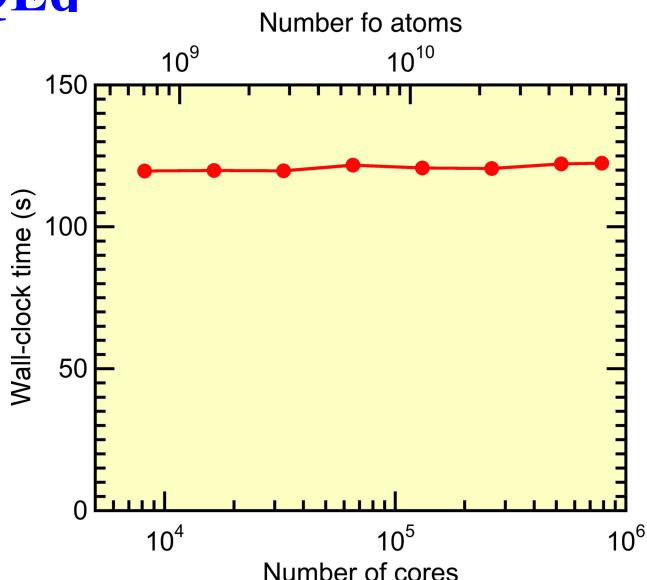
- Eliminated speed-limiting iteration for charge-equilibration (QE_q) in ReaxFF by adapting an extended-Lagrangian scheme proposed for QMD

$$L_{\text{XRMD}} = L_{\text{RMD}} + \frac{\mu}{2} \sum_i \dot{\theta}_i^2 - \frac{\mu\omega^2}{2} \sum_i (\theta_i - q_i)^2$$

Auxiliary charge:
dynamic variable

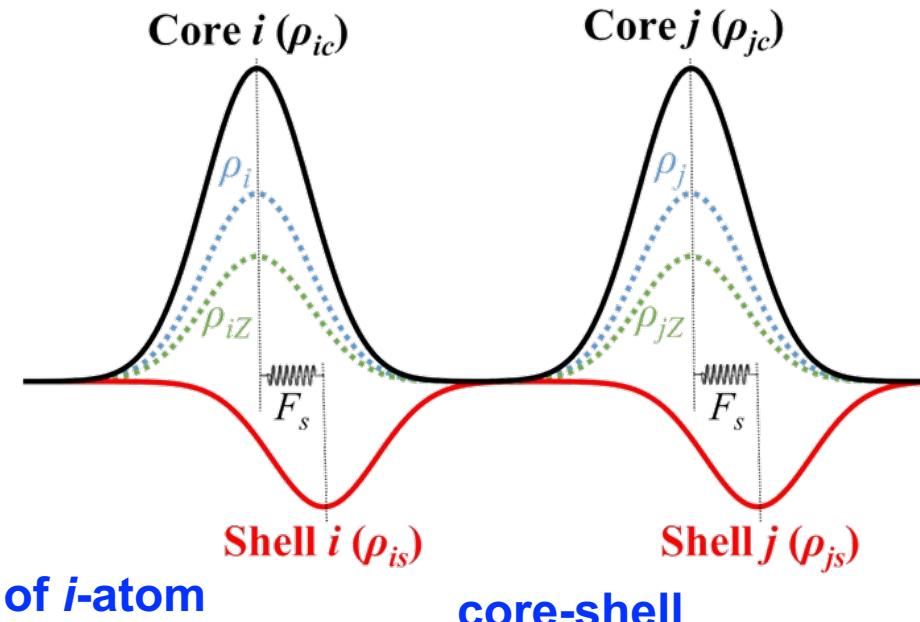
Physical charge

- Extended-Lagrangian RXMD achieves 8.6x speed up with the same energy conservation as fully converged QE_a
- Parallel efficiency 0.977 on 786,432 BlueGene/Q cores for 67.6 billion atoms



Polarizable Charge Equilibration (PQEeq) Method

- PQEeq method has been implemented in RXMD to study dielectric response as a function of time, electric field and temperature.
- Each atom is partitioned into two charged sites, i.e., core and shell
- The core consists of variable charge ρ_i and with fixed charge ρ_{iz}
- The shell is connected with the core by an isotropic harmonic spring with force constant F_s

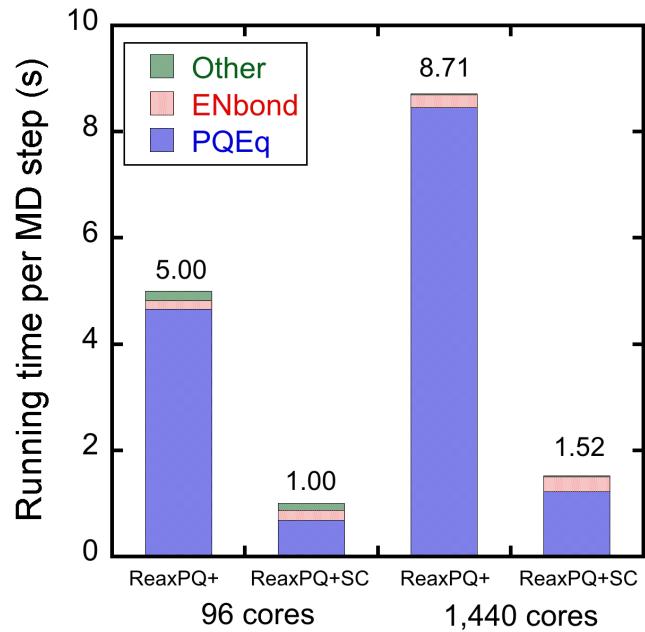
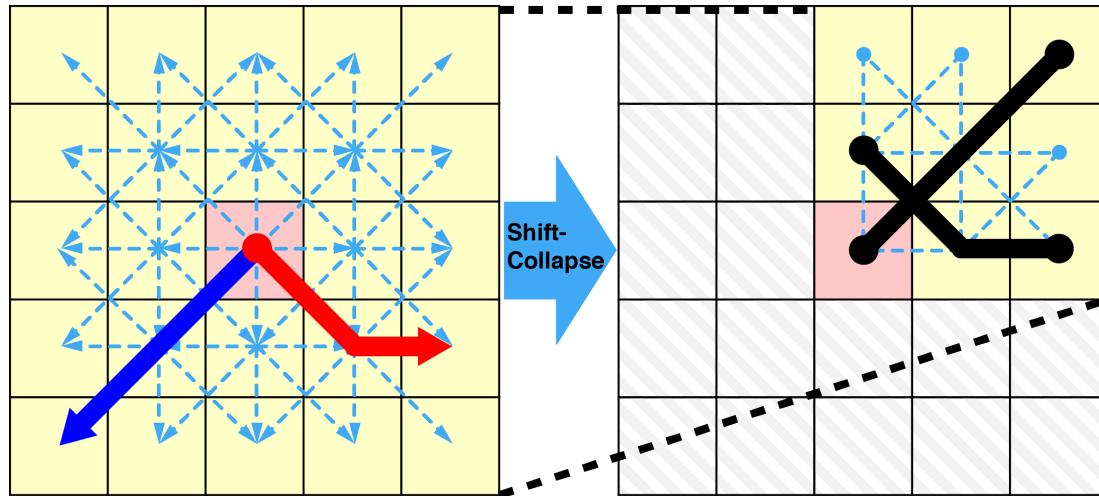


$$\begin{aligned}
 E(\{\vec{r}_{ic}, \vec{r}_{is}, q_i\}) = & \sum_i^N \left\{ E_i^0 + \chi_i^0 q_i + \frac{1}{2} J_{ii}^0 q_i^2 + \boxed{\frac{1}{2} K_s r_{ic,is}^2} \right\} \\
 & + \sum_{i>j} \left[C(\vec{r}_{ic,jc}) q_{ic} q_{jc} - C(\vec{r}_{ic,js}) q_{ic} Z_j - C(\vec{r}_{is,jc}) q_{jc} Z_i + C(\vec{r}_{is,js}) Z_i Z_j \right]
 \end{aligned}$$

core-shell interaction between *i*- and *j*-atoms

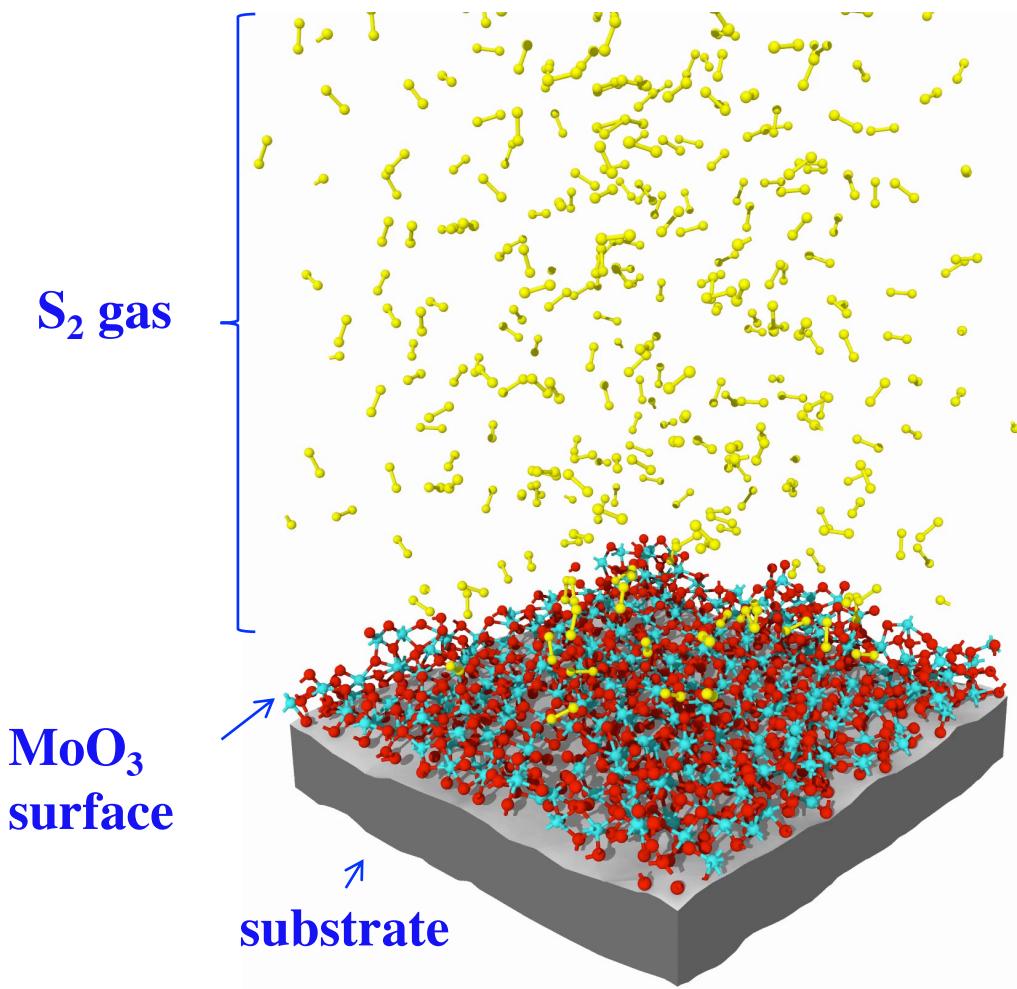
core-shell interaction on *i*-atom

Shift-Collapse (SC) Algorithm for Time-to-Solution



- SC algorithm generates optimal computation pattern for general finite-range n -tuple energy/force computations.
- SC-accelerated PQEq+SC achieves 5.0x speedup compare to the original PQEq.

RMD Simulations of MoS₂ Monolayer Synthesis



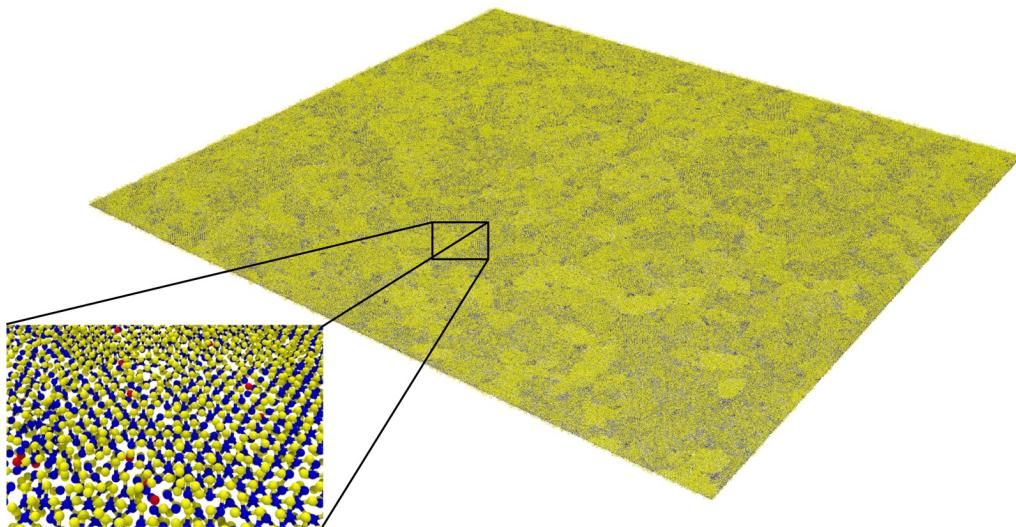
High-temperature
sulfurdization of MoO₃
monolayer with S₂ gas

**Step 1. O₂ evolution
from a MoO₃ surface**

**Step 2. SO/SO₂
formation from a
MoO_{2.6} surface**

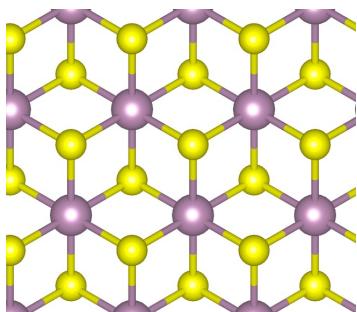
**Step 3. Mo-S bond
formation on MoO_xS_y**

MoS₂ Crystal Growth Simulation

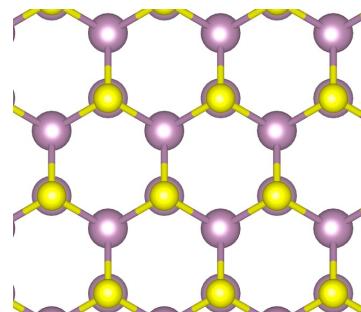


- Number of atoms:
4,305,600 atoms (1,497,600 O; 2,347,200 S and 460,800 Mo)
- System dimensions:
 $211.0 \times 196.3 \times 14.5$ (nm³)
- Timestep: 0.75 fs.

1T Structure



2H Structure

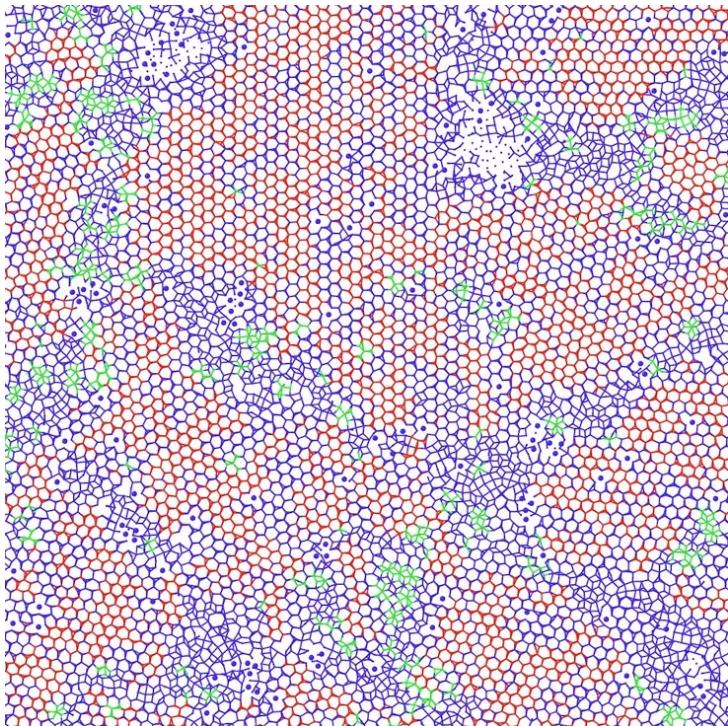


Yellow circle: Sulfur

Purple circle: Molybdenum

The pre-sulfurized MoS slab is thermalized at 3000K for 1 nsec, quenched to 1000K, then subjected to temperature cycle to improve its crystallinity.

Grain Growth by Annealing

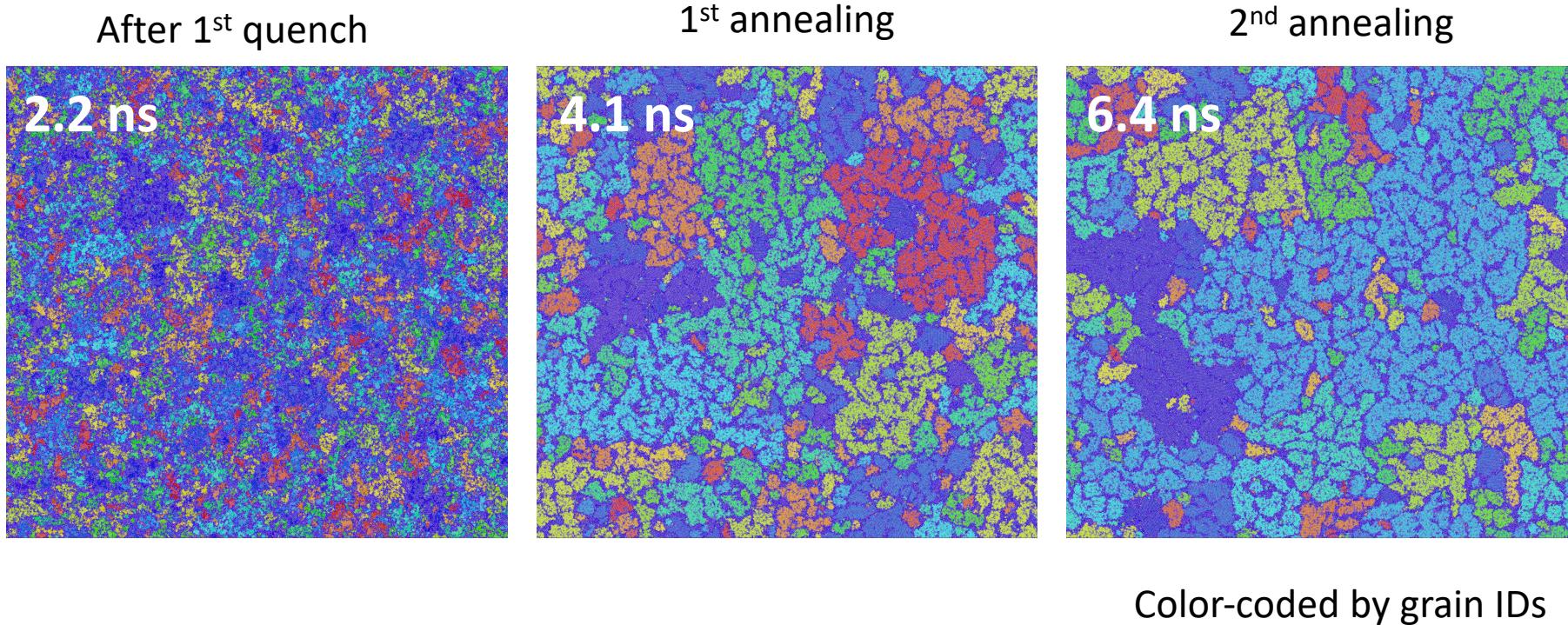


Zoom view

● 1T ● 2H ● disordered

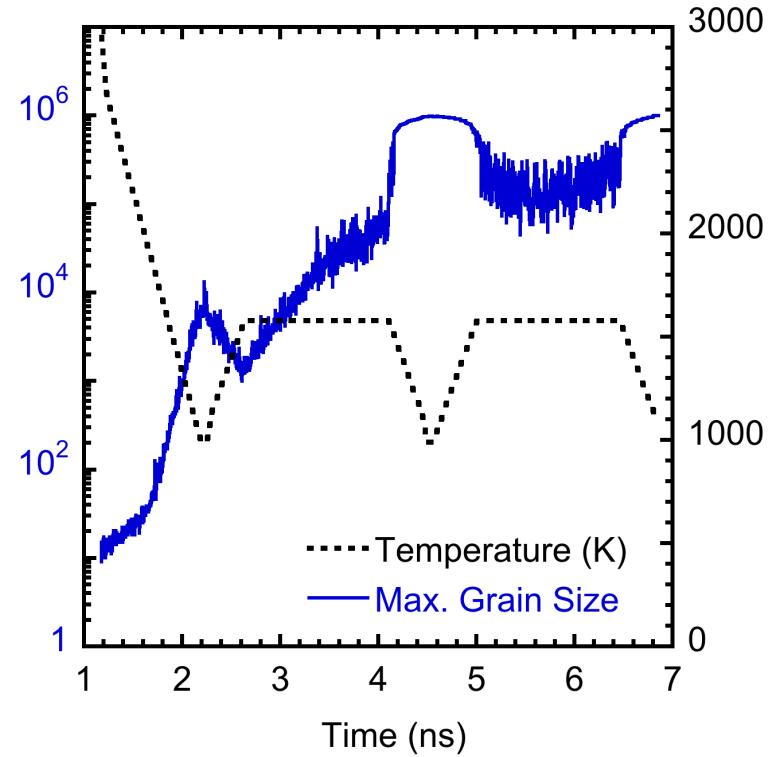
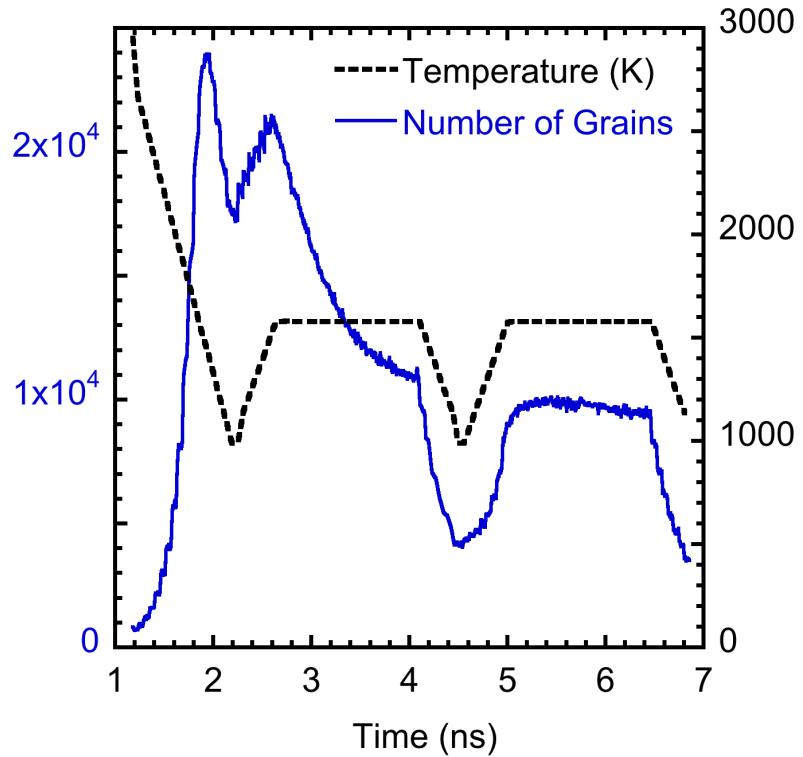
- Atoms in the slab are classified into 1T, 2H and disordered phases.
- Areas of connected 2H phase atoms indicates MoS₂ crystal grains, separated by 1T or disordered phases.

Grain Growth by Annealing



- Highly disordered structure is obtained by the rapid quenching at 2.2ns.
- Grain growth and crystallinity improvement at 6.4 ns due to the active grain boundary migration.

Grain Growth by Annealing



- Rapid decrease in the number of grains and increase in the size of grain during the 1st annealing.
- The largest grain continues to grow with a lower rate during the 2nd annealing step.

Moving Forward

Review: The ReaxFF reactive force-field: development, applications and future directions*

<https://www.nature.com/articles/npjcompumats201511>

List of published ReaxFF force fields

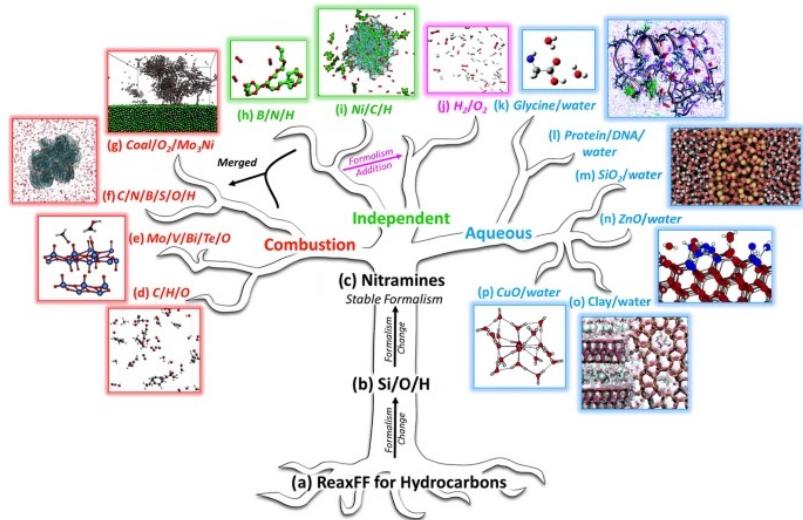
https://www.scm.com/doc/ReaxFF/Included_Forcefields.html

Interatomic potential repository

<https://www.ctcms.nist.gov/potentials/>

Recent advances in RMD:

- eReaxFF: A Pseudoclassical Treatment of Explicit Electrons within Reactive Force Field Simulations <https://pubs.acs.org/doi/10.1021/acs.jctc.6b00432>
- JAX-ReaxFF: A Gradient Based Framework for Extremely Fast Optimization of Reactive Force Fields <https://chemrxiv.org/engage/chemrxiv/article-details/60e0d9496b8d89786e6b8a06>
- Machine learning potentials for extended systems: a perspective <https://link.springer.com/article/10.1140/epjb/s10051-021-00156-1>



ReaxFF development tree*