

Kinetic Monte Carlo Simulation

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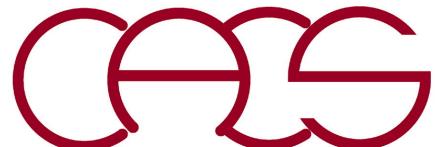
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Goal: Predicting long-time dynamics



What to Learn with Monte Carlo

- Stochastic approaches to obtain approximate solutions to intractable computational problems
- Probability-distribution sampling by Markov-chain (or Metropolis) Monte Carlo (MC) algorithm

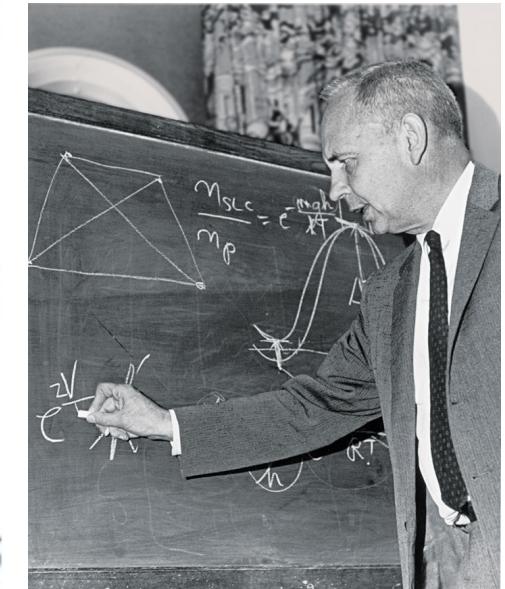
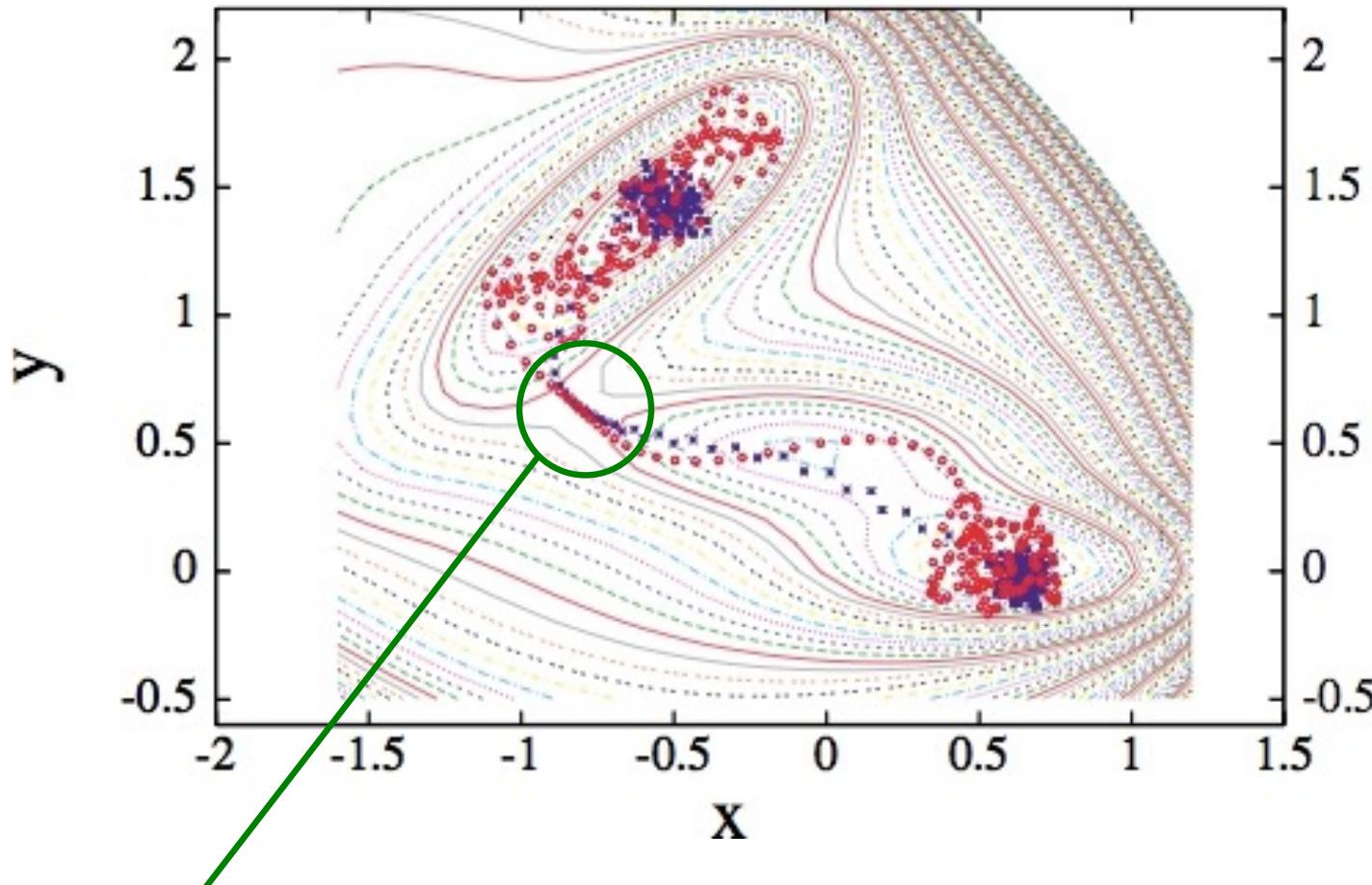
<https://aiichironakano.github.io/cs653/06MCbasics.pdf>

1. Random state change
 2. Conditional acceptance with probability $\exp(-\Delta V/k_B T)$
- Applied to simulated annealing (SA) for *global optimization*
 - Kinetic Monte Carlo (KMC) to predict *long-time dynamics*

1. Pick the next event i proportional to its transition rate r_i
 2. Advance the time by $-\ln(\text{random}\# \in [0,1]) / \sum_k r_k$
 - Divide-&-conquer KMC algorithm for scalable parallel computing

Rare Events

- Infrequent transitions from a local minimum to another local minimum



- Transition state theory to understand chemical reaction rates:
Michael Polanyi & Henry Eyring in 1920's & 1930's
- Renewed interests in understanding self-organization (protein folding, life, etc.)

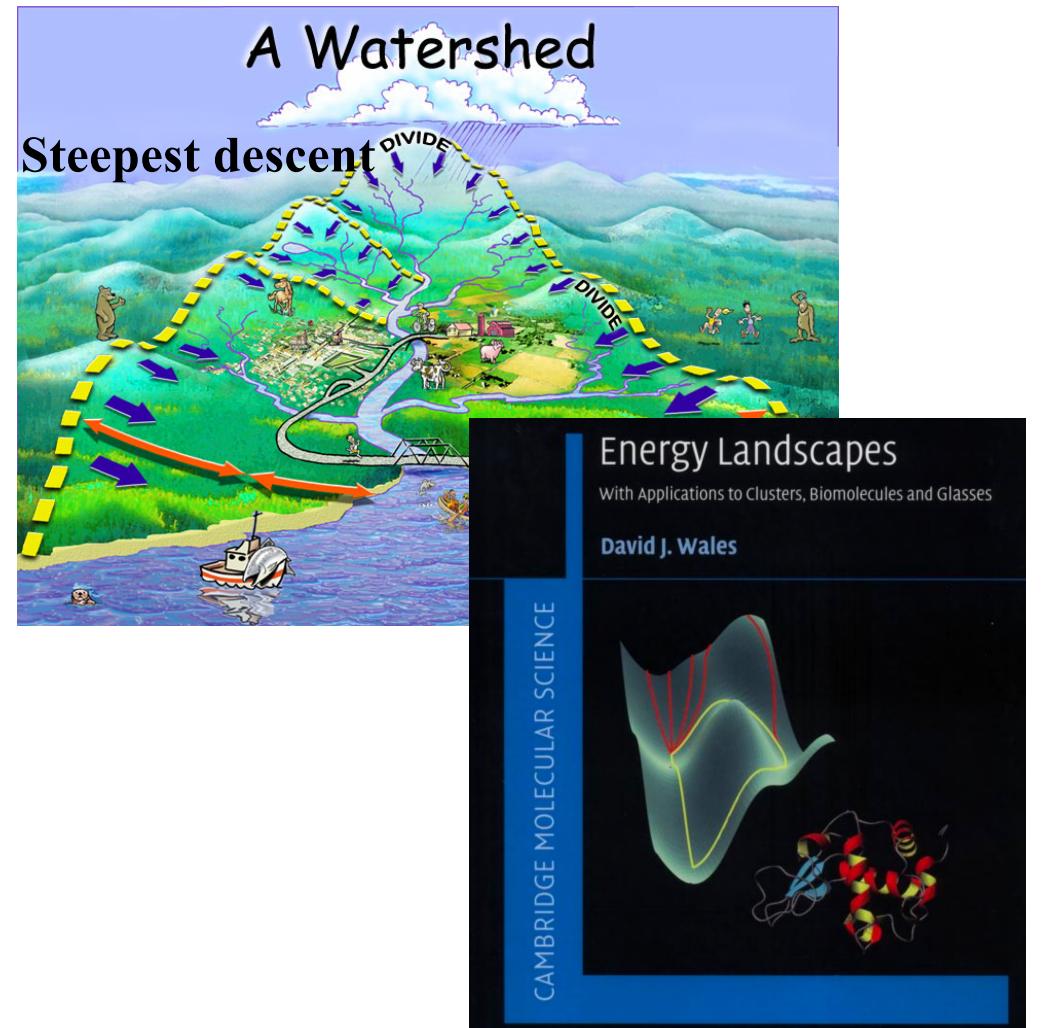
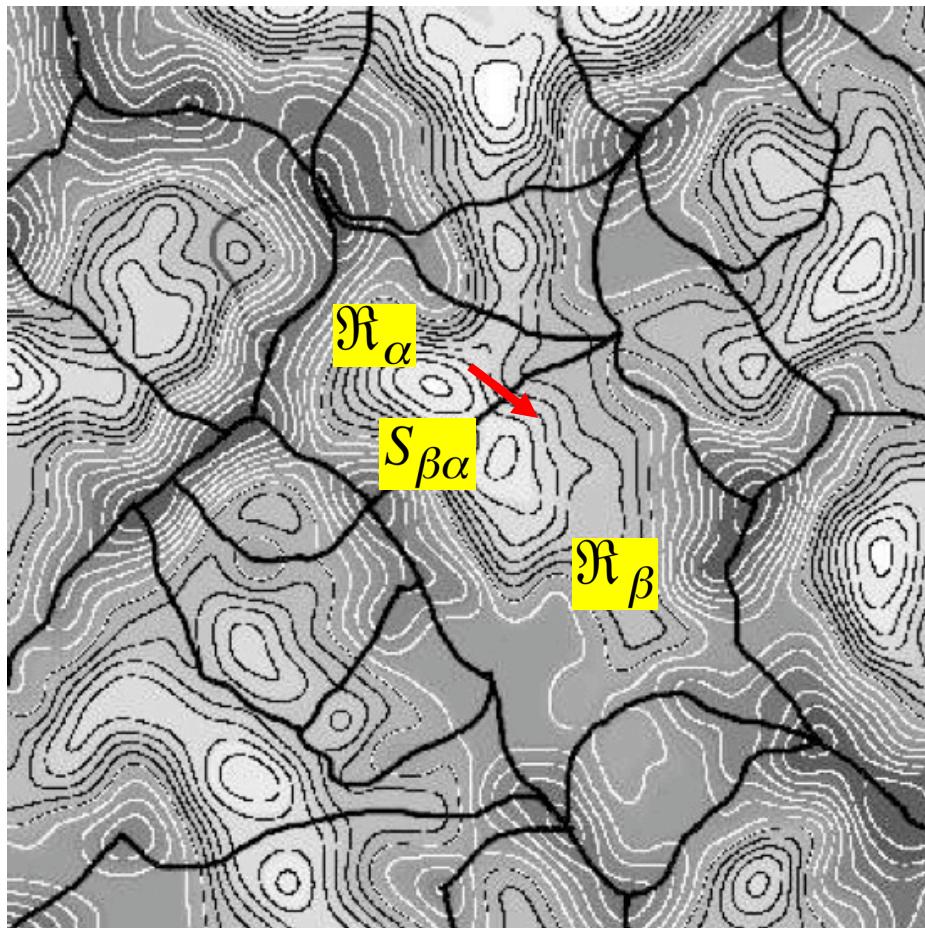
cf. H. Ostrom et al., Science 347, 978 ('15)

Energy Landscape

- Discrete abstraction: Partitioned configuration space

$$\mathfrak{R}^{3N} = \bigcup_{\alpha} \mathfrak{R}_{\alpha}; \mathfrak{R}_{\alpha} \cap \mathfrak{R}_{\alpha} = \emptyset$$

where a $3N$ -dimensional configuration $q \in \mathfrak{R}_{\alpha}$ converges to the α -th local minimum upon local minimization (N is the number of atoms)



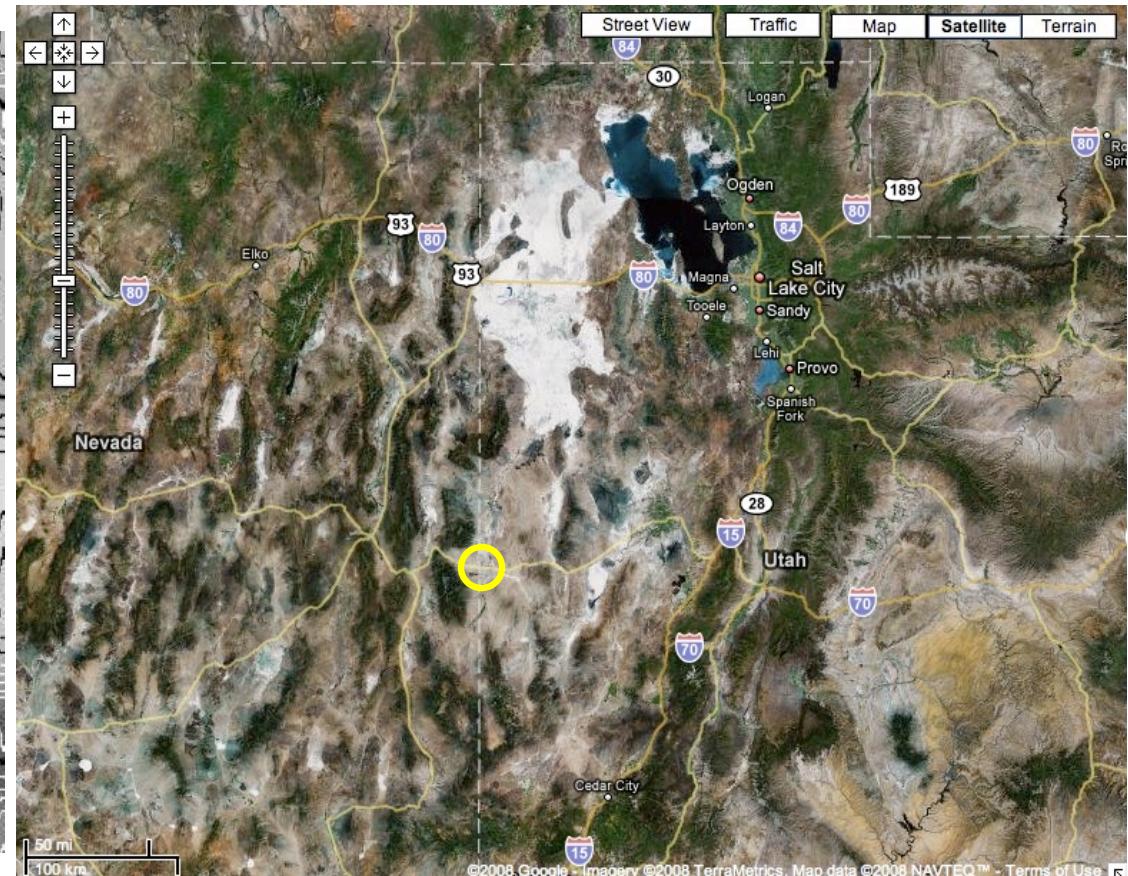
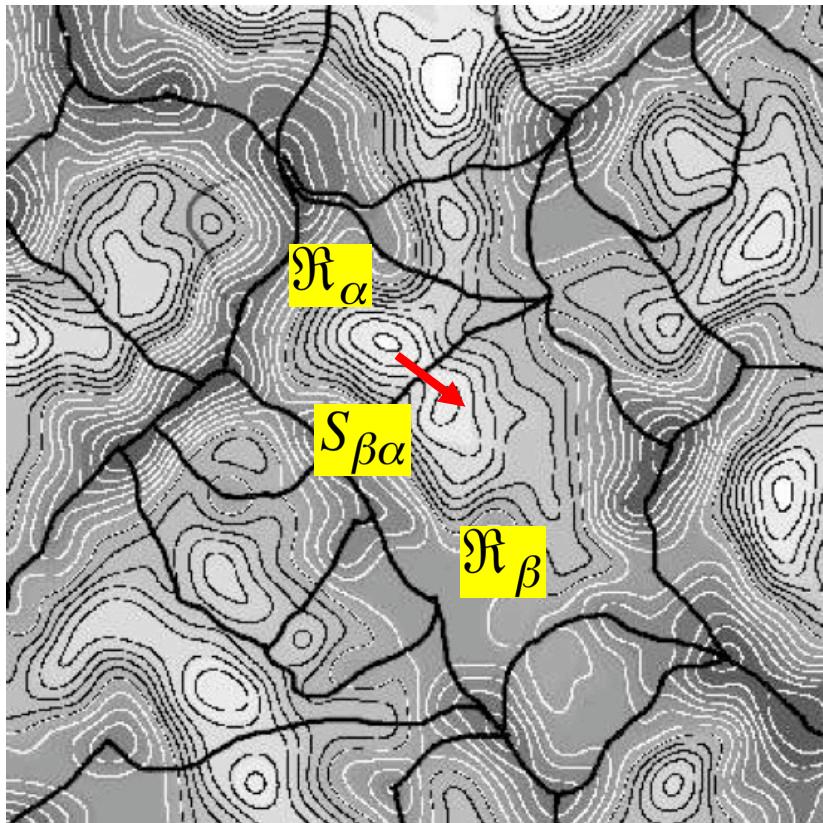
Phase Space Distribution

- Phase-space distribution $f(q, p, t)$: probability to find the system at $3N$ -dim. position $\mathbf{q} = (q_1, \dots, q_N)$ & $3N$ -dim. momentum $\mathbf{p} = (p_1, \dots, p_N)$ at time t
- Probability to find the system in \mathfrak{R}_α at time t (\hbar is the Planck constant)

$$P_\alpha(t) = \frac{1}{h^{3N}} \int_{\mathfrak{R}_\alpha} d\mathbf{q} \int d\mathbf{p} f(q, p, t)$$

cf. Plane-wave basis

$$\sum_k = \frac{L}{2\pi} \int dk = \frac{L}{2\pi\hbar} \int \hbar dk = \frac{L}{\hbar} \int dp \rightarrow \frac{1}{\hbar} \int dq \int dp$$



Outline

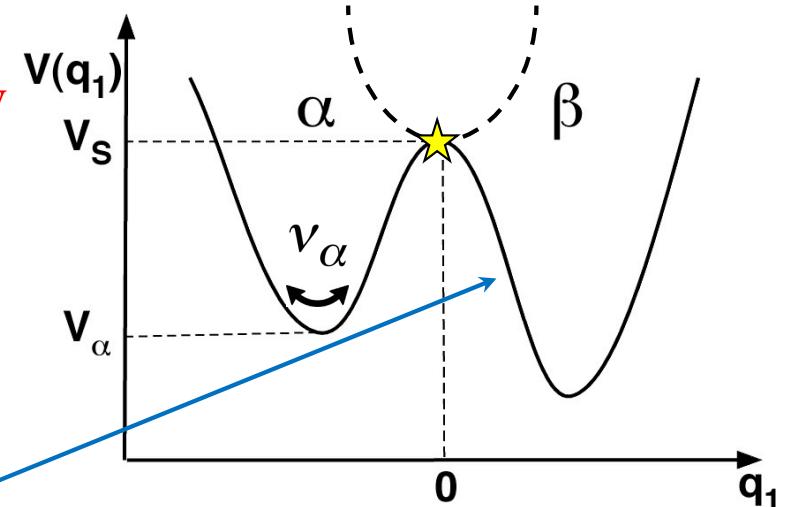
- Master equation

$$\frac{dP_\alpha}{dt} = -\sum_{\beta} W_{\beta\alpha} P_\alpha(t) + \sum_{\beta} W_{\alpha\beta} P_\beta(t) \quad W_{\beta\alpha}: \text{Transition rate from state } \alpha \text{ to state } \beta$$

- How to compute $W_{\alpha\beta}$? Transition state theory

$$W_{\beta\alpha} \approx v_\alpha \exp\left(-\frac{V_s - V_\alpha}{k_B T}\right)$$

Vibration frequency at the
 α -th local minimum



Minimum energy path along a saddle point (transition state)

- How to simulate the master equation: Kinetic Monte Carlo simulation

Let $\{r_1, r_2, \dots\}$ be a set of possible escape events,
 $r = \sum_i r_i$, and u_1 & u_2 are uniform random
numbers in $[0,1]$:

1. Pick the next event i as $i = \min_j \left\{ \sum_{k=1}^j \frac{r_k}{r} > u_1 \right\}$
2. Advance the time by $t = -\ln(u_2)/r$



Dynamics of Phase Space Distribution

- Phase-space distribution $f(\mathbf{q}, \mathbf{p}, t)$: probability to find the system at $3N$ -dim. position $\mathbf{q} = (q_1, \dots, q_N)$ & $3N$ -dim. momentum $\mathbf{p} = (p_1, \dots, p_N)$ at time t
- Probability to find the system in \mathfrak{R}_α at time t (\hbar is the Planck constant)

$$P_\alpha(t) = \frac{1}{\hbar^{3N}} \int_{\mathfrak{R}_\alpha} d\mathbf{q} \int d\mathbf{p} f(q, p, t)$$

- Time derivative (L = Liouville operator; $H(\mathbf{q}, \mathbf{p})$ = Hamiltonian)

$$\begin{aligned} \frac{dP_\alpha}{dt} &= \frac{1}{\hbar^{3N}} \int_{\mathfrak{R}_\alpha} d\mathbf{q} \int d\mathbf{p} \frac{\partial}{\partial t} f(q, p, t) \\ &= \frac{1}{\hbar^{3N}} \int_{\mathfrak{R}_\alpha} d\mathbf{q} \int d\mathbf{p} [-Lf(q, p, t)] \\ &= \frac{1}{\hbar^{3N}} \int_{\mathfrak{R}_\alpha} d\mathbf{q} \int d\mathbf{p} \left[-\left(\frac{\partial H}{\partial \mathbf{p}} \bullet \frac{\partial}{\partial \mathbf{q}} - \frac{\partial H}{\partial \mathbf{q}} \bullet \frac{\partial}{\partial \mathbf{p}} \right) f(q, p, t) \right] \end{aligned}$$

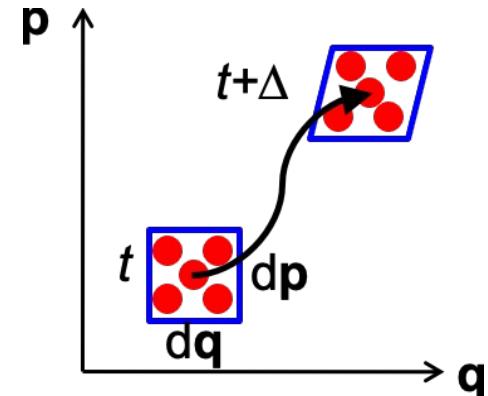
See supplementary note 1: [Liouville equation](#)

Sketch of Proof: Liouville Operator

$$\frac{d}{dt} \tilde{\mathbf{X}}^{(\mathbf{q}, \mathbf{p})} = \dot{\mathbf{X}} \cdot \frac{\partial}{\partial \mathbf{X}} = \dot{\mathbf{q}} \cdot \frac{\partial}{\partial \mathbf{q}} + \dot{\mathbf{p}} \cdot \frac{\partial}{\partial \mathbf{p}} = \frac{\partial H}{\partial \mathbf{p}} \cdot \frac{\partial}{\partial \mathbf{q}} - \frac{\partial H}{\partial \mathbf{q}} \cdot \frac{\partial}{\partial \mathbf{p}}$$

Jacobian: Volume magnification factor $\left| \frac{\partial \mathbf{X}_t}{\partial \mathbf{X}_0} \right| d\mathbf{X}_0 = d\tilde{\mathbf{X}}_t$

Probability density as point crowd
 $N_{\text{sample}} f_0(\mathbf{X}_0) d\mathbf{X}_0 = N_{\text{sample}} f(\mathbf{X}_t, t) d\tilde{\mathbf{X}}_t$



Liouville's theorem

$$\left| \frac{\partial \mathbf{X}_t}{\partial \mathbf{X}_0} \right| = 1$$

Liouville lecture, p. 4

$$(1 + \delta t)^{\frac{1}{\delta t}} \xrightarrow[\delta t \rightarrow 0]{} e$$

$$(1 + \delta t^2)^{\frac{1}{\delta t}} \xrightarrow[\delta t \rightarrow 0]{} 1$$

$$\frac{f(\mathbf{X}, dt) + \dot{\mathbf{X}} dt \cdot \frac{\partial f}{\partial \mathbf{X}}}{f(\mathbf{X} + \dot{\mathbf{X}} dt, dt)} = f(\mathbf{X}, 0)$$

$$\therefore \frac{f(\mathbf{X}, dt) - f(\mathbf{X}, 0)}{dt} = -\dot{\mathbf{X}} \cdot \frac{\partial f}{\partial \mathbf{X}} = -Lf$$

$$\text{or } \left(\frac{\partial}{\partial t} + L \right) f = 0$$

$$\frac{\partial}{\partial t} f(\mathbf{X}, t) + \frac{\partial}{\partial \mathbf{X}} \cdot (\dot{\mathbf{X}} f) = 0 \quad (\mathbf{X} = (\mathbf{q}, \mathbf{p}) \in \mathfrak{R}^{6N})$$

$$cf. \frac{\partial}{\partial t} \rho + \nabla \cdot \vec{j} = 0 \quad (\text{mass conservation})$$

$$f(x) = \ln(1 + x) = 0 \ (x = 0); \frac{df}{dx} = \frac{1}{1+x} = 1 \ (x = 0)$$

$$\therefore \ln(1 + x) = f(0) + \frac{df}{dx} \Big|_{x=0} x + \dots = x + \dots$$

$$\ln(1 + \delta t)^{\frac{1}{\delta t}} = \frac{1}{\delta t} \ln(1 + \delta t) \xrightarrow[\delta t \rightarrow 0]{} \frac{1}{\delta t} \delta t = 1$$

$$\therefore (1 + \delta t)^{\frac{1}{\delta t}} \xrightarrow[\delta t \rightarrow 0]{} e$$

$$\ln(1 + \delta t^2)^{\frac{1}{\delta t}} = \frac{1}{\delta t} \ln(1 + \delta t^2) \xrightarrow[\delta t \rightarrow 0]{} \frac{1}{\delta t} \delta t^2 = 0$$

$$\therefore (1 + \delta t^2)^{\frac{1}{\delta t}} \xrightarrow[\delta t \rightarrow 0]{} 1$$

population flux

Liouville lecture, p. 6

Population Dynamics

- Let

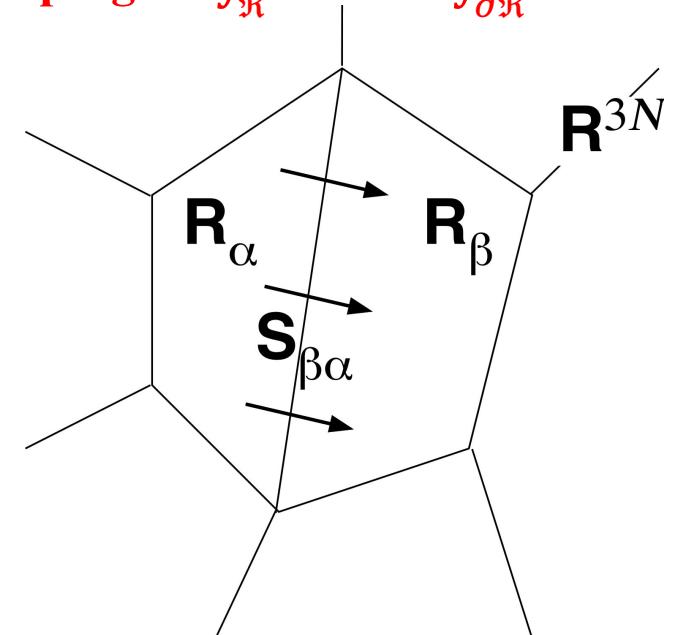
$$H(\mathbf{q}, \mathbf{p}) = \sum_{i=1}^{3N} \frac{p_i^2}{2m_i} + V(\mathbf{q})$$

then

Note $\int_{-\infty}^{\infty} dp_i \frac{\partial}{\partial p_i} f(p_i) = [f(p_i)]_{-\infty}^{\infty} = 0$ (telescoping)

$$\begin{aligned} \frac{dP_\alpha}{dt} &= -\frac{1}{h^{3N}} \int d\mathbf{q} \int d\mathbf{p} \sum_{i=1}^{3N} \frac{p_i}{m_i} \frac{\partial}{\partial q_i} f(\mathbf{q}, \mathbf{p}, t) + \frac{1}{h^{3N}} \int d\mathbf{q} \int d\mathbf{p} \sum_{i=1}^{3N} \frac{\partial V}{\partial q_i} \frac{\partial}{\partial p_i} f(\mathbf{q}, \mathbf{p}, t) \\ &= -\frac{1}{h^{3N}} \int d\mathbf{q} \int d\mathbf{p} \sum_{i=1}^{3N} \frac{\partial}{\partial q_i} \left(\frac{p_i}{m_i} f(\mathbf{q}, \mathbf{p}, t) \right) \\ &= -\frac{1}{h^{3N}} \int_{\partial \mathfrak{R}_\alpha} \sum_{i=1}^{3N} dS_i \int d\mathbf{p} \sum_{i=1}^{3N} \frac{p_i}{m_i} f(\mathbf{q}, \mathbf{p}, t) \end{aligned}$$

Gauss' theorem
~ telescoping $\int_{\mathfrak{R}} d\mathbf{q} \nabla = \int_{\partial \mathfrak{R}} d\mathbf{S}$



where $d\mathbf{S}$ is the surface element pointing outward normal to the surface $\partial \mathfrak{R}_\alpha$ that outlines \mathfrak{R}_α

- dP_α/dt is negative of the outward flux through $\partial \mathfrak{R}_\alpha$

$$\int dq \frac{\partial}{\partial q} f = [f]_{\text{lower}}^{\text{upper}} = f dS_+ + f dS_-$$



Population Flux

- Partition the surface $\partial\mathfrak{R}_\alpha$ into

$$\partial\mathfrak{R}_\alpha = \sum_\beta S_{\beta\alpha}$$

where $S_{\beta\alpha}$ is the surface splitting \mathfrak{R}_α & \mathfrak{R}_β (normal pointing from α to β)

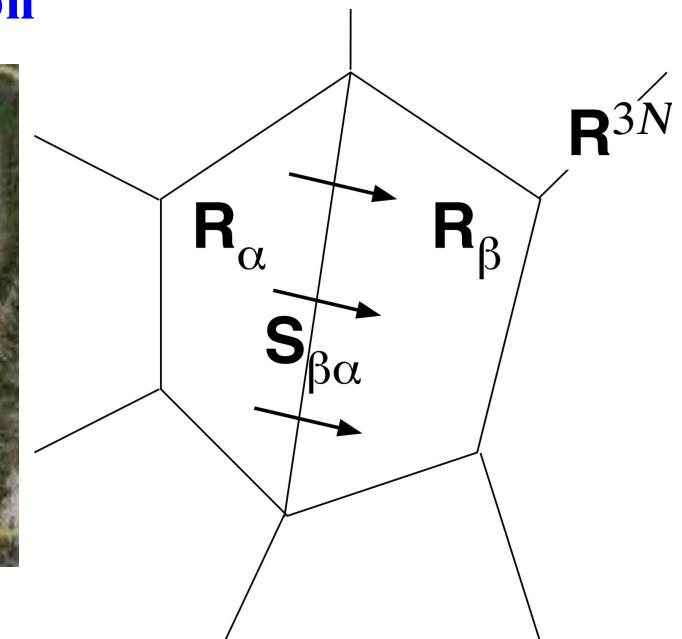
$$\frac{dP_\alpha}{dt} = -\sum_\beta \frac{1}{h^{3N}} \int_{S_{\beta\alpha}} \sum_{i=1}^{3N} dS_i \int d\mathbf{p} \sum_{i=1}^{3N} \frac{p_i}{m_i} \Theta\left(\sum_i dS_i \frac{p_i}{m_i}\right) f(\mathbf{q}, \mathbf{p}, t) \text{ outgoing}$$

Partition of unity

$$\Theta(x) + \Theta(-x) = 1$$

$$+ \sum_\beta \frac{1}{h^{3N}} \int_{S_{\alpha\beta}} \sum_{i=1}^{3N} dS_i \int d\mathbf{p} \sum_{i=1}^{3N} \frac{p_i}{m_i} \Theta\left(\sum_i dS_i \frac{p_i}{m_i}\right) f(\mathbf{q}, \mathbf{p}, t) \text{ incoming}$$

where $\Theta(x) = 1 (x \geq 0)$ & $0 (x < 0)$ is the step function



Local Equilibration Approximation

- Assume that within each \mathfrak{R}_α , the phase space distribution is locally in thermal equilibrium, weighted to reproduce the current population (time scale of inter-state population transfer \gg intra-state thermal equilibration time)

$$f(\mathbf{q}, \mathbf{p}, t) \cong \frac{P_\alpha(t)}{P_\alpha(\text{eq})} f_{\text{eq}}(\mathbf{q}, \mathbf{p})$$

where

$$f_{\text{eq}}(\mathbf{q}, \mathbf{p}) = \frac{1}{Q} \exp(-H(\mathbf{q}, \mathbf{p})/k_B T)$$

and the partition function is split into

$$Q = \iint \frac{d\mathbf{q} d\mathbf{p}}{h^{3N}} \exp(-H(\mathbf{q}, \mathbf{p})/k_B T) = \sum_\alpha \iint_{\mathfrak{R}_\alpha} \frac{d\mathbf{q} d\mathbf{p}}{h^{3N}} \exp(-H(\mathbf{q}, \mathbf{p})/k_B T) = \sum_\alpha Q_\alpha$$

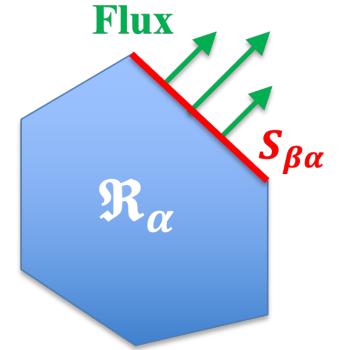
$$\therefore P_\alpha(\text{eq}) = \frac{Q_\alpha}{Q} = \frac{1}{Q} \iint_{\mathfrak{R}_\alpha} \frac{d\mathbf{q} d\mathbf{p}}{h^{3N}} \exp(-H(\mathbf{q}, \mathbf{p})/k_B T)$$

Master Equation

- Substituting the local-equilibration approximation into the population-flux equation, we obtain

$$\frac{dP_\alpha}{dt} = -\sum_{\beta} \frac{1}{h^{3N}} \int_{S_{\beta\alpha}} \sum_{i=1}^{3N} dS_i \int d\mathbf{p} \sum_{i=1}^{3N} \frac{p_i}{m_i} \Theta\left(\sum_i dS_i \frac{p_i}{m_i}\right) f_{eq}(\mathbf{q}, \mathbf{p}) \frac{P_\alpha(t)}{P_\alpha(\text{eq})}$$

$$+ \sum_{\beta} \frac{1}{h^{3N}} \int_{S_{\alpha\beta}} \sum_{i=1}^{3N} dS_i \int d\mathbf{p} \sum_{i=1}^{3N} \frac{p_i}{m_i} \Theta\left(\sum_i dS_i \frac{p_i}{m_i}\right) f_{eq}(\mathbf{q}, \mathbf{p}) \frac{P_\beta(t)}{P_\beta(\text{eq})}$$



$$\therefore \frac{dP_\alpha}{dt} = -\sum_{\beta} W_{\beta\alpha} P_\alpha(t) + \sum_{\beta} W_{\alpha\beta} P_\beta(t)$$

$$W_{\alpha\beta} = \frac{1}{h^{3N}} \int_{S_{\alpha\beta}} \sum_{i=1}^{3N} dS_i \int d\mathbf{p} \sum_{i=1}^{3N} \frac{p_i}{m_i} \Theta\left(\sum_i dS_i \frac{p_i}{m_i}\right) f_{eq}(\mathbf{q}, \mathbf{p}) \Bigg/ P_\beta(\text{eq}) \quad \text{Weighted average of flux on surface}$$

$$= \frac{1}{h^{3N}} \int_{S_{\alpha\beta}} \sum_{i=1}^{3N} dS_i \int d\mathbf{p} \sum_{i=1}^{3N} \frac{p_i}{m_i} \Theta\left(\sum_i dS_i \frac{p_i}{m_i}\right) e^{-H(\mathbf{q}, \mathbf{p})/k_B T} \Bigg/ \frac{1}{h^{3N}} \iint_{\mathfrak{R}_\beta} d\mathbf{q} d\mathbf{p} e^{-H(\mathbf{q}, \mathbf{p})/k_B T}$$

See supplementary note 2: Master equation

A. P. J. Jansen, Introduction to KMC Simulations of Surface Reactions (Springer, '12)

Transition State Theory

- Reaction coordinate q_1 along a minimum-energy path separates the phase space into 2 regions — A ($q_1 < 0$) & B ($q_1 > 0$); all the other coordinates & momenta are collectively denoted as $\mathbf{X} = (\mathbf{q}, \mathbf{p}) = (q_2, \dots, q_{3N}, p_2, \dots, p_{3N})$

- Probability to find the system being in B

$$P_B(t) = \iiint \frac{dq_1 dp_1 d\mathbf{X}}{h^{3N}} \Theta(q_1) f(q_1, p_1, \mathbf{X}, t)$$

- Time derivative (L = Liouville operator)

$$\frac{dP_B}{dt} = \iiint \frac{dq_1 dp_1 d\mathbf{X}}{h^{3N}} \Theta(q_1) \frac{\partial}{\partial t} f(q_1, p_1, \mathbf{X}, t)$$

$$= \iiint \frac{dq_1 dp_1 d\mathbf{X}}{h^{3N}} \Theta(q_1) (-L f(q_1, p_1, \mathbf{X}, t))$$

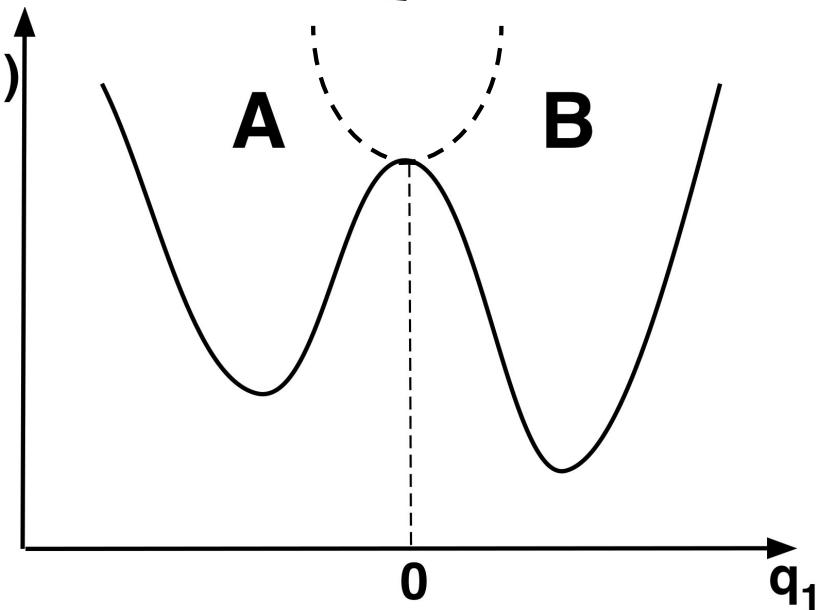
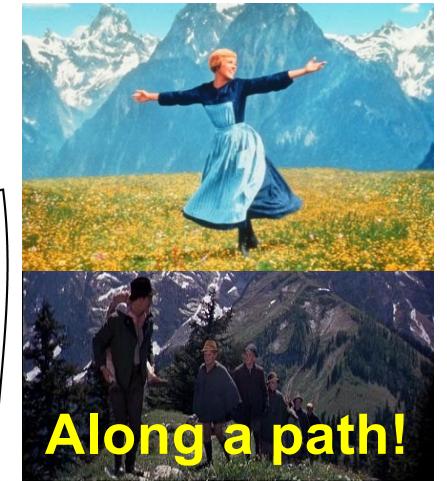
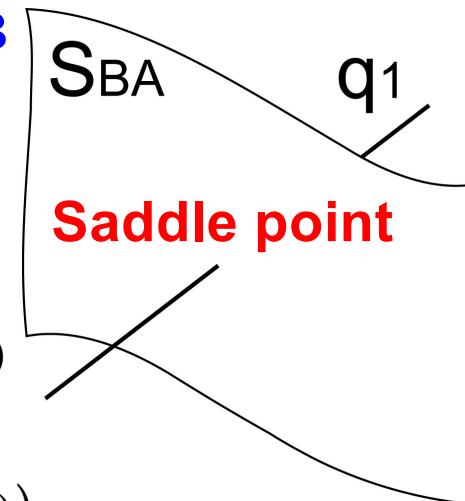
Integration by part

$$= \iiint \frac{dq_1 dp_1 d\mathbf{X}}{h^{3N}} (L \Theta(q_1)) f(q_1, p_1, \mathbf{X}, t)$$

$$= \iiint \frac{dq_1 dp_1 d\mathbf{X}}{h^{3N}} \left(\frac{p_1}{m_1} \delta(q_1) \right) f(q_1, p_1, \mathbf{X}, t)$$

$$= \iint \frac{dp_1 d\mathbf{X}}{h^{3N}} \frac{p_1}{m_1} f(0, p_1, \mathbf{X}, t)$$

Weighted average of flux on surface



Local Equilibration Approximation

- Split the integral into the gain ($A \rightarrow B$) & loss ($B \rightarrow A$) terms

$$\frac{dP_B}{dt} = \left(\frac{dP_B}{dt} \right)_{A \rightarrow B} + \left(\frac{dP_B}{dt} \right)_{B \rightarrow A} \quad \Theta(p_1) + \Theta(-p_1) = 1$$

$$= \int_0^{\infty} \frac{dp_1}{h} \int \frac{d\mathbf{X}}{h^{3N-1}} \frac{p_1}{m_1} f(0, p_1, \mathbf{X}, t) + \int_{-\infty}^0 \frac{dp_1}{h} \int \frac{d\mathbf{X}}{h^{3N-1}} \frac{p_1}{m_1} f(0, p_1, \mathbf{X}, t)$$

- Regions A & B locally (i.e., within the region) maintain the equilibrium distribution weighted to reproduce the current population

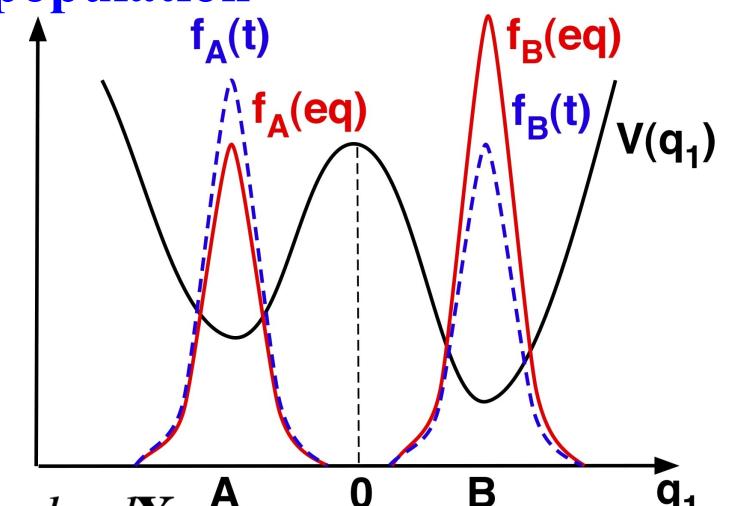
$$f_{\alpha, \text{local}} \approx \frac{P_{\alpha}(t)}{P_{\alpha}(\text{eq})} f_{\text{eq}} \quad (\alpha = A, B)$$

$$f_{\text{eq}} = \frac{1}{Q} \exp(-H/k_B T)$$

$$Q = \iiint \frac{dq_1 dp_1 d\mathbf{X}}{h^{3N}} \exp(-H/k_B T) = Q_A + Q_B$$

$$Q_A = \iiint_{q_1 < 0} \frac{dq_1 dp_1 d\mathbf{X}}{h^{3N}} \exp(-H/k_B T) \quad Q_B = \iiint_{q_1 > 0} \frac{dq_1 dp_1 d\mathbf{X}}{h^{3N}} \exp(-H/k_B T)$$

$$P_{\alpha}(\text{eq}) = \frac{Q_{\alpha}}{Q} \quad (\alpha = A, B)$$



Transition State Theory

- Substituting the local equilibration approximation to the flux equation

$$\left(\frac{dP_B}{dt} \right)_{A \rightarrow B} = \int_0^{\infty} \frac{dp_1}{h} \int \frac{d\mathbf{X}}{h^{3N-1}} \frac{p_1}{m_1} f_{\text{eq}}(0, p_1, \mathbf{X}) \frac{P_A(t)}{P_A(\text{eq})}$$

$$\left(\frac{dP_B}{dt} \right)_{B \rightarrow A} = - \int_0^{\infty} \frac{dp_1}{h} \int \frac{d\mathbf{X}}{h^{3N-1}} \frac{p_1}{m_1} f_{\text{eq}}(0, p_1, \mathbf{X}) \frac{P_B(t)}{P_B(\text{eq})}$$

$$\therefore \frac{dP_B(t)}{dt} = k_{BA} P_A(t) - k_{AB} P_B(t)$$

$$k_{BA} = \int_0^{\infty} \frac{dp_1}{h} \int \frac{d\mathbf{X}}{h^{3N-1}} \frac{p_1}{m_1} f_{\text{eq}}(0, p_1, \mathbf{X}) \frac{1}{P_A(\text{eq})}$$

$$k_{AB} = \int_0^{\infty} \frac{dp_1}{h} \int \frac{d\mathbf{X}}{h^{3N-1}} \frac{p_1}{m_1} f_{\text{eq}}(0, p_1, \mathbf{X}) \frac{1}{P_B(\text{eq})}$$

- Analytical integration over p_1

$$k_{BA} = \int_0^{\infty} \frac{dp_1}{h} \frac{p_1}{m_1} \exp\left(-p_1^2 / 2m_1 k_{\text{B}} T\right) \int \frac{d\mathbf{X}}{h^{3N-1}} \frac{\exp(-H / k_{\text{B}} T)_{q_1=p_1=0}}{Q} \frac{Q}{Q_A} = \frac{k_{\text{B}} T}{h} \frac{Q^*}{Q_A}$$

$$Q^* = \int \frac{d\mathbf{X}}{h^{3N-1}} \exp(-H / k_{\text{B}} T)_{q_1=p_1=0}$$

$k_{\text{B}} T / h \sim 10^{13} \text{ s}^{-1}$
at room temperature

Harmonic Transition State Theory

- In region A, we assume

$$V(q_1, \dots, q_{3N}) = V_A + \frac{1}{2} \sum_j m_j (\omega_j^A)^2 (q_j - b_j)^2$$

$$\therefore Q_A = \left(\frac{2\pi k_B T}{h} \right)^{3N} \frac{\exp(-V_A/k_B T)}{\prod_{j=1}^{3N} \omega_j^A}$$

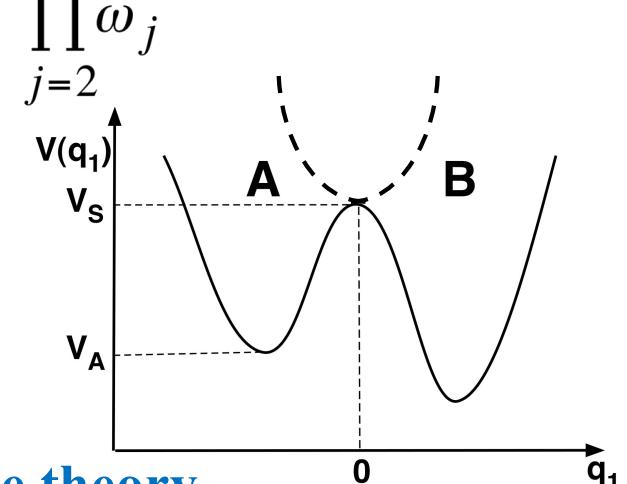
- At the dividing surface, we assume

$$V(q_1, \dots, q_{3N}) = V_S - \frac{1}{2} a_{11} q_1^2 + \frac{1}{2} \sum_{j=2}^{3N} m_j (\omega_j^*)^2 q_j^2$$

$$Q^* = \int \frac{d\mathbf{X}}{h^{3N-1}} \exp(-H/k_B T)_{q_1=p_1=0} = \left(\frac{2\pi k_B T}{h} \right)^{3N-1} \frac{\exp(-V_s/k_B T)}{\prod_{j=2}^{3N} \omega_j^*}$$

$$\therefore k_{BA} = \frac{1}{2\pi} \exp\left(-\frac{V_s - V_A}{k_B T}\right) \frac{\prod_{j=1}^{3N} \omega_j^A}{\prod_{j=2}^{3N} \omega_j^*} \cong \boxed{\frac{\omega_1^A}{2\pi}} \exp\left(-\frac{V_s - V_A}{k_B T}\right)$$

attempt frequency
acceptance probability



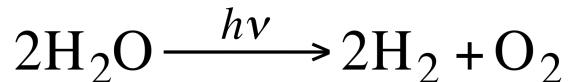
See supplementary note 3: Transition state theory

Digression: Save the World?

- Solar land-area requirement (with 10% energy conversion efficiency) to supply the global energy Nathan Lewis, Caltech



- Need better catalyst for splitting water Lewis & Nocera, PNAS 103, 15729 ('06)



COMPUTATIONAL METHODS

A search engine for catalysts

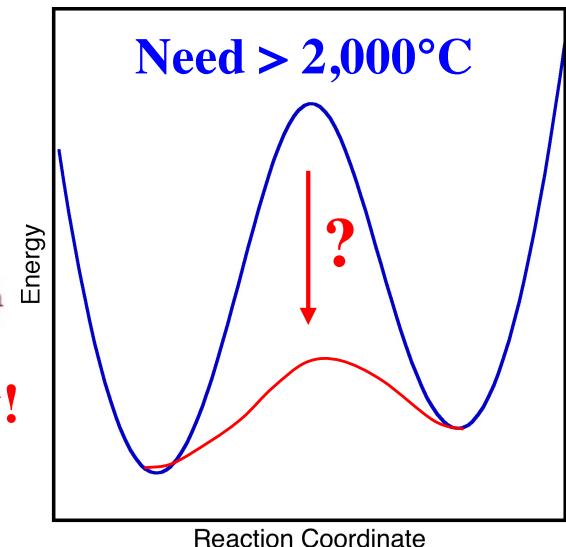
Trial and error has been the traditional method of finding the best catalyst for a reaction. A computational approach can reduce the lab work required.

Just bring down the transition-state energy!

Nature Mater. 5, 847 ('06)

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Hydrogen Production@Home



A Job for Superatom

PRL 104, 126102 (2010)

PHYSICAL REVIEW LETTERS

week ending
26 MARCH 2010

Molecular Dynamics Simulations of Rapid Hydrogen Production from Water Using Aluminum Clusters as Catalysts

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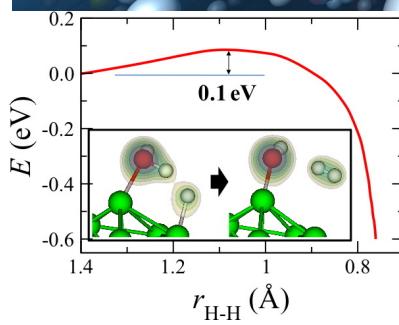
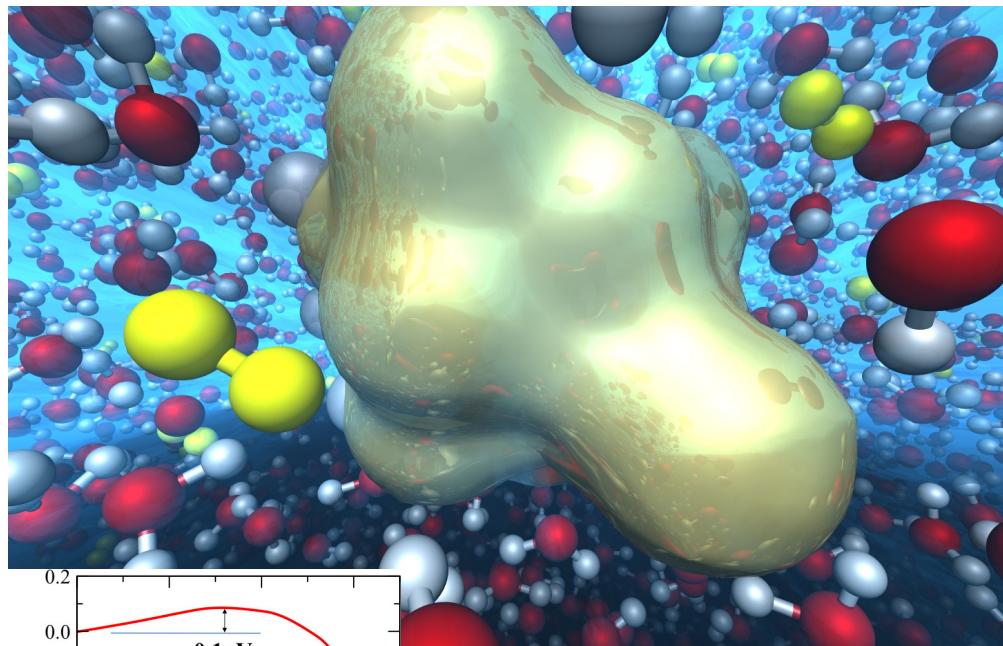
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(Received 1 December 2009; published 26 March 2010)

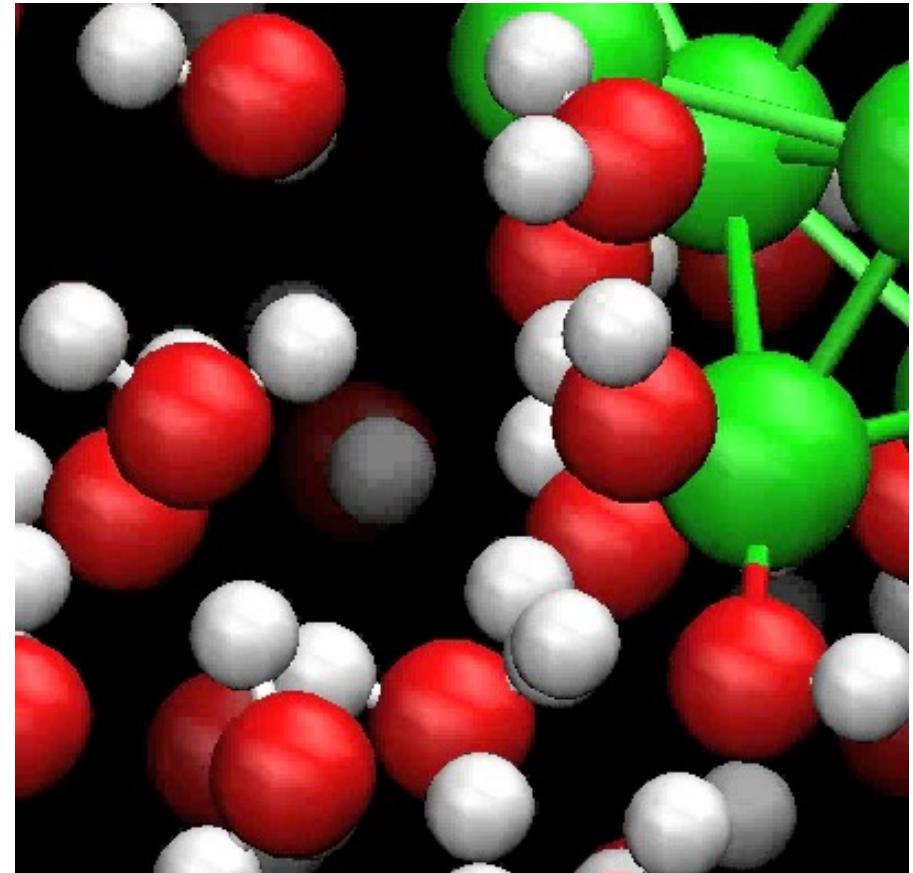
$$k_B T_{\text{room}}/h \sim 10^{13} (\text{s}^{-1})$$

$$1 \text{ eV}/k_B \sim 10,000 \text{ K}$$

$$e^{-x} \sim 10^{-x/2}$$

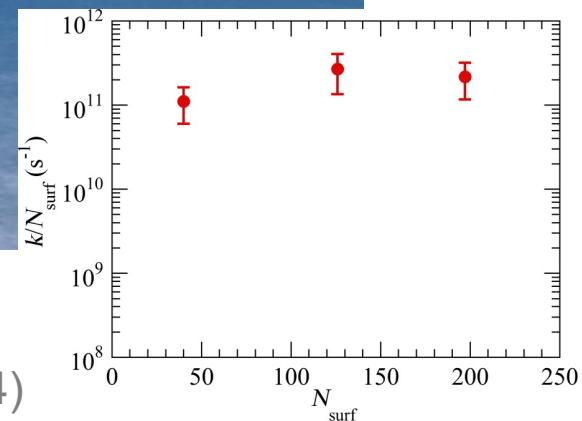
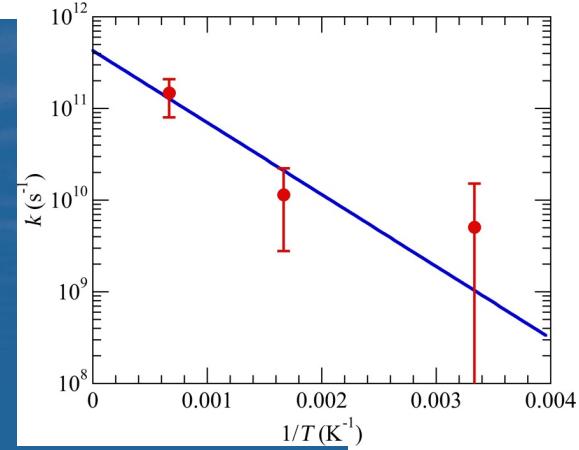
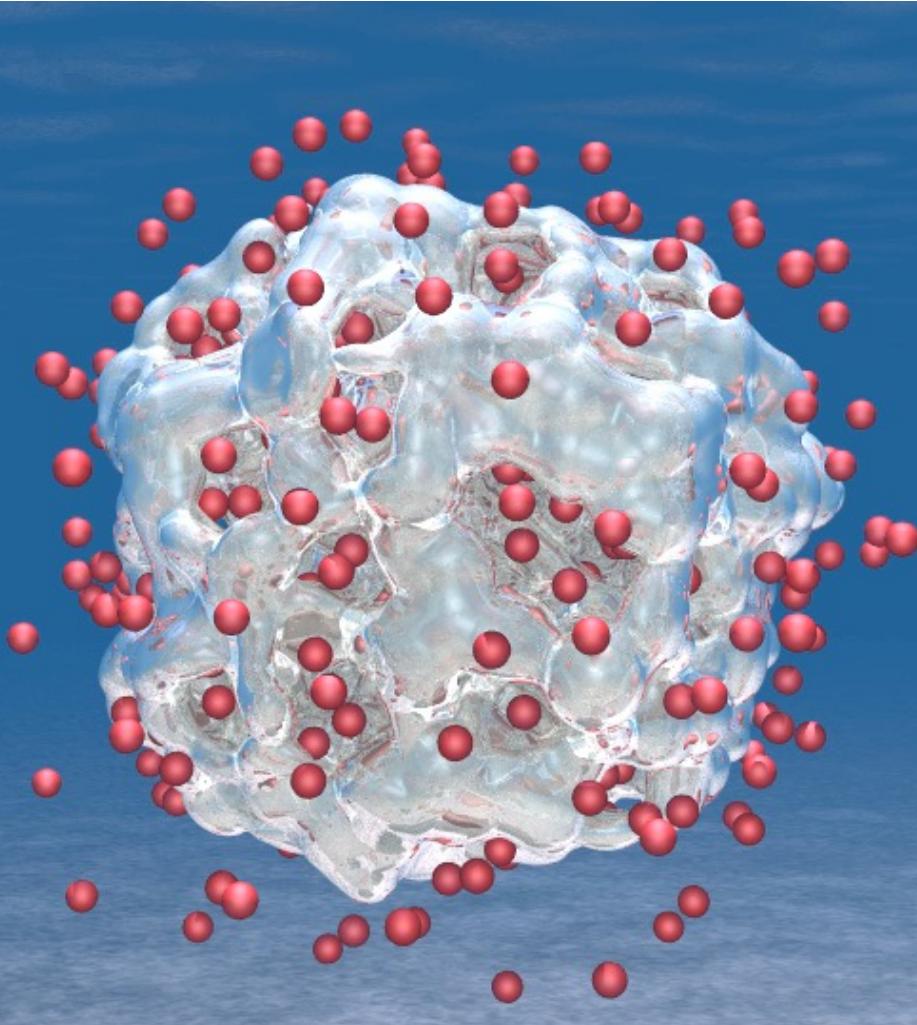


$$\begin{aligned} k_{\text{H}_2} &= \frac{k_B T}{h} \exp\left(-\frac{\Delta}{k_B T_{\text{room}}}\right) \\ &= 10^{11} (\text{s}^{-1}) \end{aligned}$$



H_2 Production from Water Using LiAl Particles

16,661-atom QMD simulation of $Li_{441}Al_{441}$ in water
on 786,432 IBM Blue Gene/Q cores

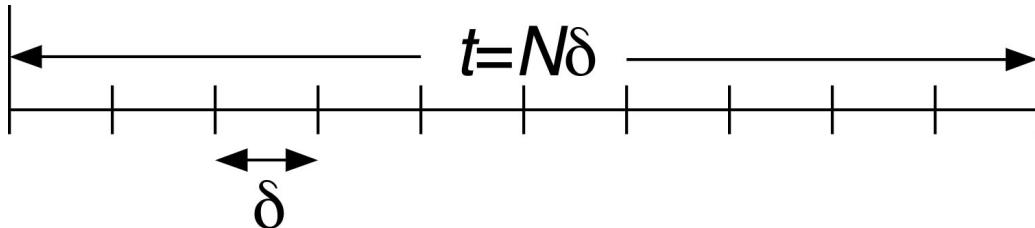


- Scalable to industrially relevant particle sizes

K. Shimamura *et al.*, *Nano Lett.* **14**, 4090 ('14)

Poisson Process

- Poisson process = sequence of events, in which the probability of an event to occur in time $[t, t+\delta]$ is $r\delta$ (r is the rate) independent of history as $\delta \rightarrow 0$
- Probability $P(n,t)$ that n events occur in time interval $t=N\delta$



$$P(n,t) = C(N,n)(r\delta)^n (1 - r\delta)^{N-n} = \frac{N!}{n!(N-n)!} (r\delta)^n (1 - r\delta)^{N-n}$$

$$\xrightarrow[N \rightarrow \infty]{} \frac{(rt)^n}{n!} e^{-rt}$$

$$\therefore \begin{cases} (1 - rt/N)^{N/rt} \xrightarrow[N \rightarrow \infty]{} e^{-1} & \lim_{N \rightarrow \infty} \left(1 \pm \frac{1}{N}\right)^N = e^{\pm 1} \\ N! \xrightarrow[N \rightarrow \infty]{} \sqrt{2\pi N} N^N e^{-N} & \because \ln \left(1 \pm \frac{1}{N}\right)^N = N \ln \left(1 \pm \frac{1}{N}\right) \\ & \xrightarrow[N \rightarrow \infty]{} N \left(\pm \frac{1}{N}\right) = \pm 1 \end{cases}$$

- Sum rule:

$$\sum_{n=0}^{\infty} P(n,t) = \sum_{n=0}^{\infty} \frac{(rt)^n}{n!} e^{-rt} = 1$$

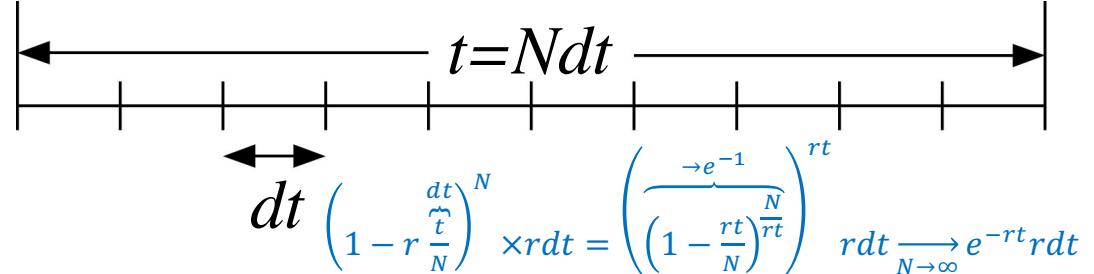
Kinetic Monte Carlo Simulation

- Probability density $P(t)$ of time t between successive events

$P(t)dt = \text{probability}(\text{no event in } [0,t] \wedge 1 \text{ event in } [t,t+dt])$

$$= P(0,t) \times rdt = e^{-rt} \times rdt$$

$$\therefore P(t) = re^{-rt}$$



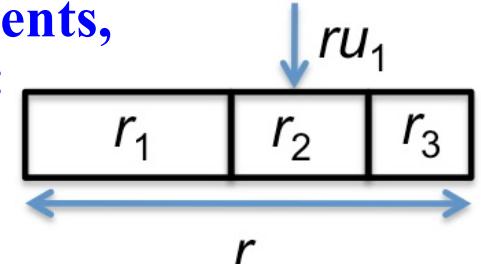
- Random time-interval generation: Let u be a uniform random number in $[0,1]$ & generate $t = -\ln(u)/r \in [0,\infty]$

$$\therefore P(t) = P(u) \left| \frac{du}{dt} \right| = 1 \times re^{-rt} = re^{-rt}$$

- Kinetic MC algorithm: Let $\{r_1, r_2, \dots\}$ be a set of possible events, $r = \sum_i r_i$, and u_1 & u_2 are uniform random numbers in $[0,1]$:

- Pick the next event i as $i = \min_j \left\{ \sum_{k=1}^j \frac{r_k}{r} > u_1 \right\}$
Pick i -th event with probability $p_i = r_i/r$

- Advance the time by $t = -\ln(u_2)/r$



$$P(t)dt = \underbrace{e^{-rt}}_{\text{no evt in } [0,t]} \underbrace{\frac{1}{(r_1 + r_2 + \dots)dt}}_{\text{evt 1 or 2 or ... in } [t,t+dt]}$$

K. A. Fichthorn & W. H. Weinberg, *J. Chem. Phys.* **95**, 1090 ('91)

See supplementary note 4: Kinetic Monte Carlo simulation

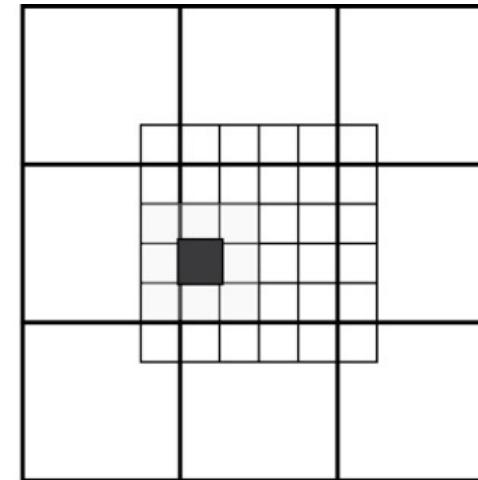
Divide-&-Conquer KMC Algorithm

- **Domain decomposition:** Concurrent events among multiple domains, d

$$\Delta t = -\ln(rnd) / \sum_d r_d = O(N^{-1}) \Rightarrow -\ln(rnd) / \max_d (r_d) = O(1)$$

- **Colored domain blocks:** Avoids conflicting events by allowing concurrent events only with domains of the same color, which are well-separated

1	3	1	3	1	3
0	2	0	2	0	2
1	3	1	3	1	3
0	2	0	2	0	2
1	3	1	3	1	3
0	2	0	2	0	2



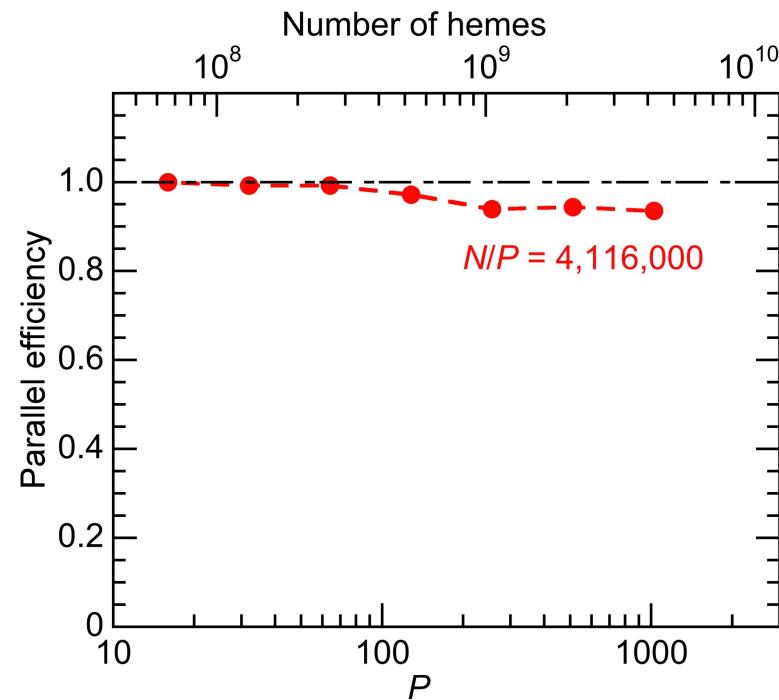
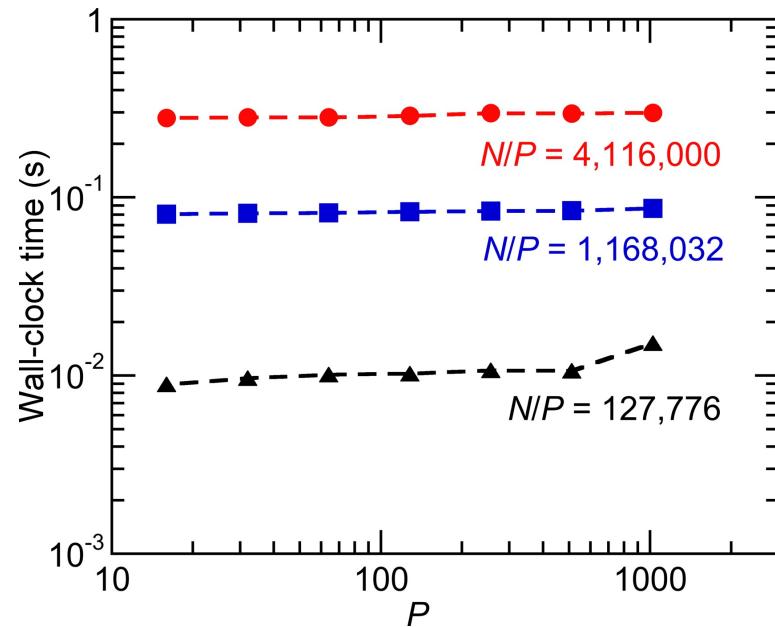
E. Martinez et al., J. Comp. Phys. 230, 1359 ('11)

- **Neighbor-domain caching for spatial decomposition via message-passing**
- **Dual linked-list cell method:** (1) small cells for constructing neighbor lists for nearest-neighbor hopping events; (2) large cells for domain-block coloring

H. Byun et al., Comput. Phys. Commun. 219, 246 ('17)

Scalable Parallel KMC

- Benchmark tests on electron transfer in heme aggregates
- Better weak-scaling for coarser granularity (N hemes on P processors)



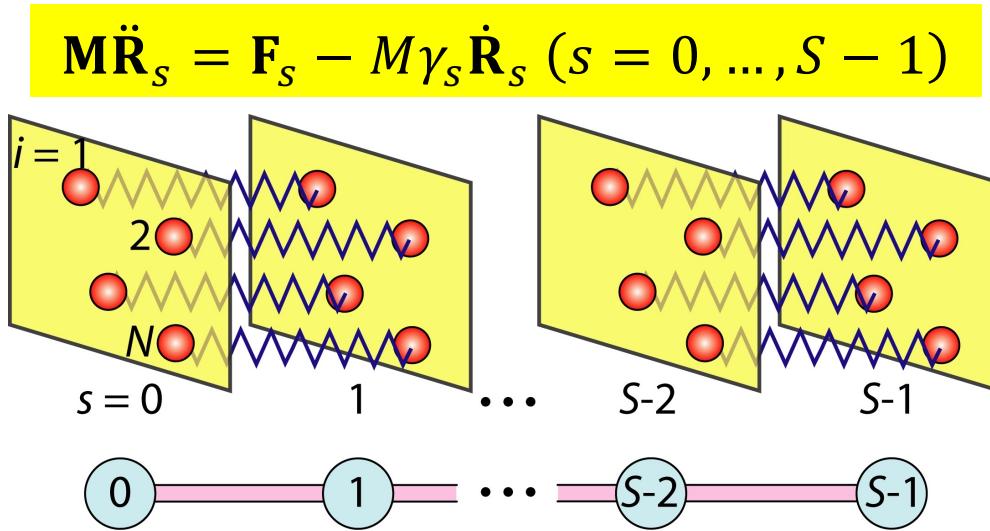
- Weak-scaling parallel efficiency 0.935 for a 4.2 billion-heme system on 1,024 Intel Xeon processors

Temporal Locality in Long-Time Dynamics

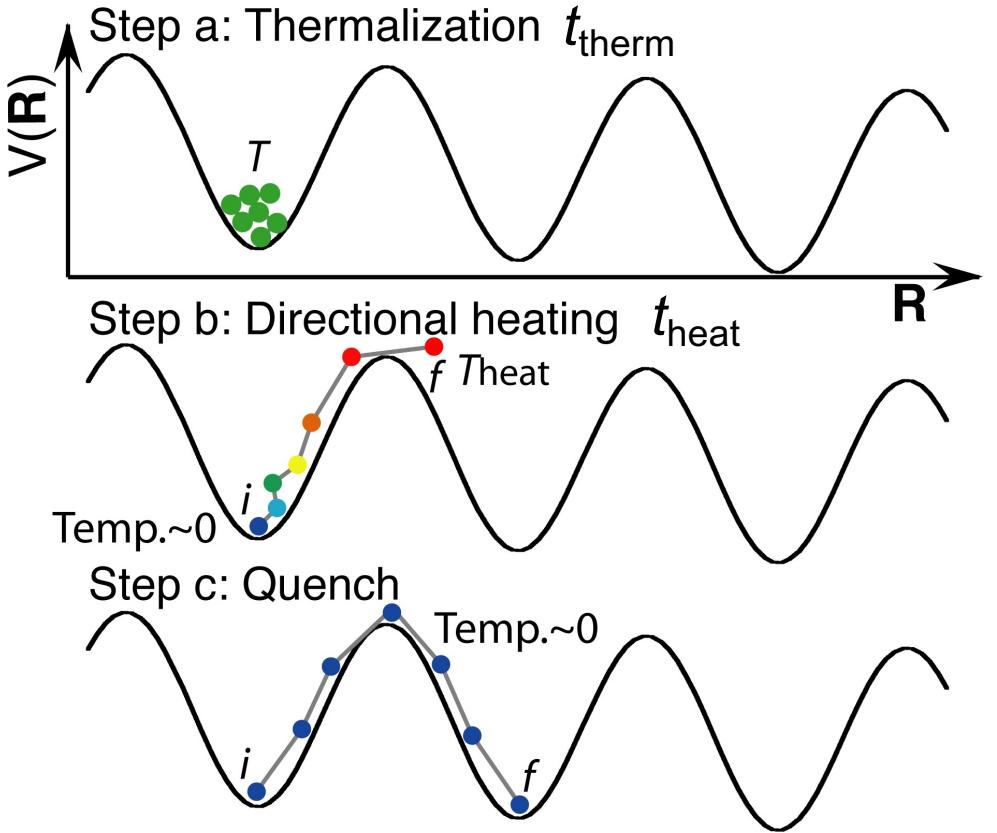
- **Temporal locality:** Rare transitions between local minimum-energy states
- **Transition state theory:** Reformulate *sequential* long-time dynamics as *parallel* search for low activation-barrier transition events
- **Discrete graph abstraction:** Linear combinations of atomistic events (LCAE)

A. Nakano, *Comput. Phys. Commun.* **176**, 292 ('07)

- **Directionally heated nudged elastic band (NEB) method:** Search for thermally activated events without the knowledge of final states



$$\mathbf{F}_s = \begin{cases} -\frac{\partial V}{\partial \mathbf{R}_s}^{\perp} + \mathbf{F}_s^{\text{spr}} & (1 \leq s \leq S-2) \\ -\frac{\partial V}{\partial \mathbf{R}_s}^{\parallel} & (s = 0, S-1) \end{cases}$$



Space-Time-Ensemble Parallel (STEP) NEB

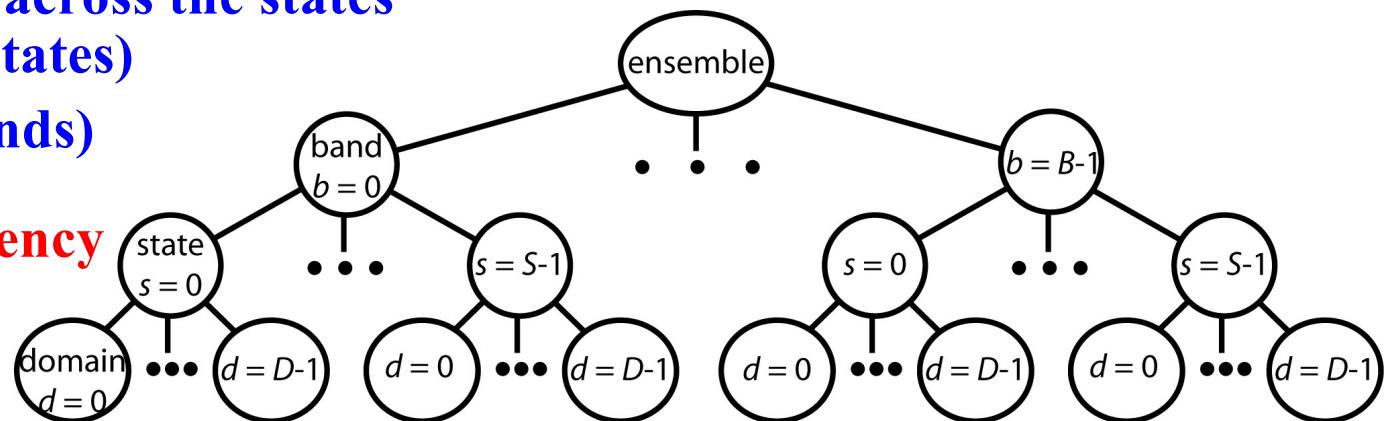
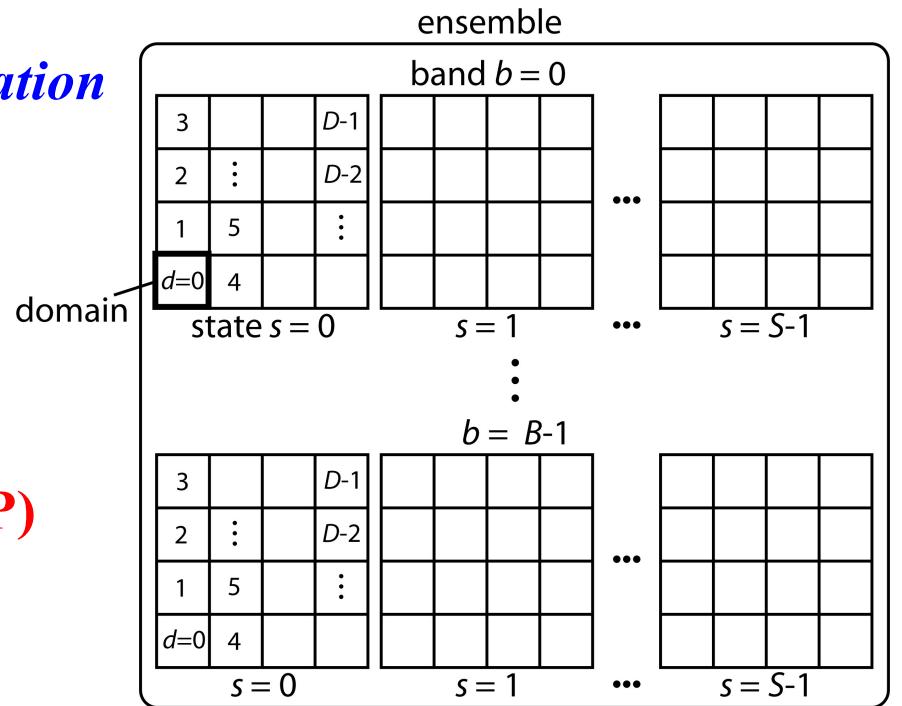
- Path ensemble method (PEM): Long-time simulation in the framework of kinetic Monte Carlo—*molecular kinetics simulation*

$$r_b = \left\{ t_{\text{therm}} + t_{\text{heat}} \exp \left[\frac{\Delta_b}{k_B} \left(\frac{1}{T} - \frac{1}{T_{\text{heat}}} \right) \right] \right\}^{-1}$$

$$P_b = \frac{r_b}{r} = \frac{r_b}{\sum_{b=0}^{B-1} r_b}$$

- Space-time-ensemble parallelism (STEP)
 - = spatial decomposition within each state (D domains)
 - + temporal parallelism across the states within each band (S states)
 - + band ensemble (B bands)
- Hierarchical concurrency

$$P = BSD$$

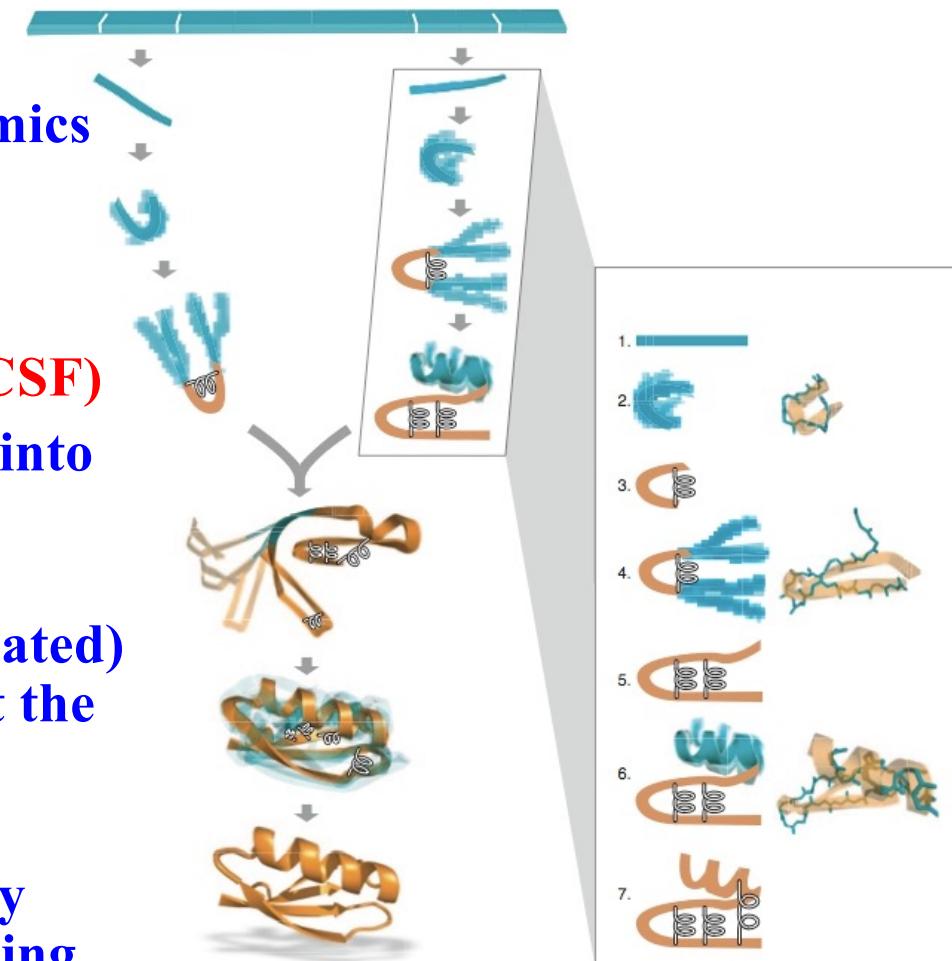


Divide-&-Conquer Protein Folding

- Levinthal paradox (1968): How the Nature folds an amino-acid sequence into a global energy minimum 3D structure (which is known to be NP complete) within microseconds (~ billion molecular-dynamics steps).
- Sequential KMC not good enough.

Zip-&-assembly algorithm (Ken Dill at UCSF)

1. **(Divide)** Chop the amino-acid sequence into ~10 residue fragments.
2. **(Conquer)** For each fragment, perform replica-exchange (~ temperature accelerated) molecular dynamics simulation & detect the formation of any stable hydrophobic contacts.
3. **(Combine)** Grow the stable fragments by adding surrounding residues while freezing (~ constraint) the found stable contacts.



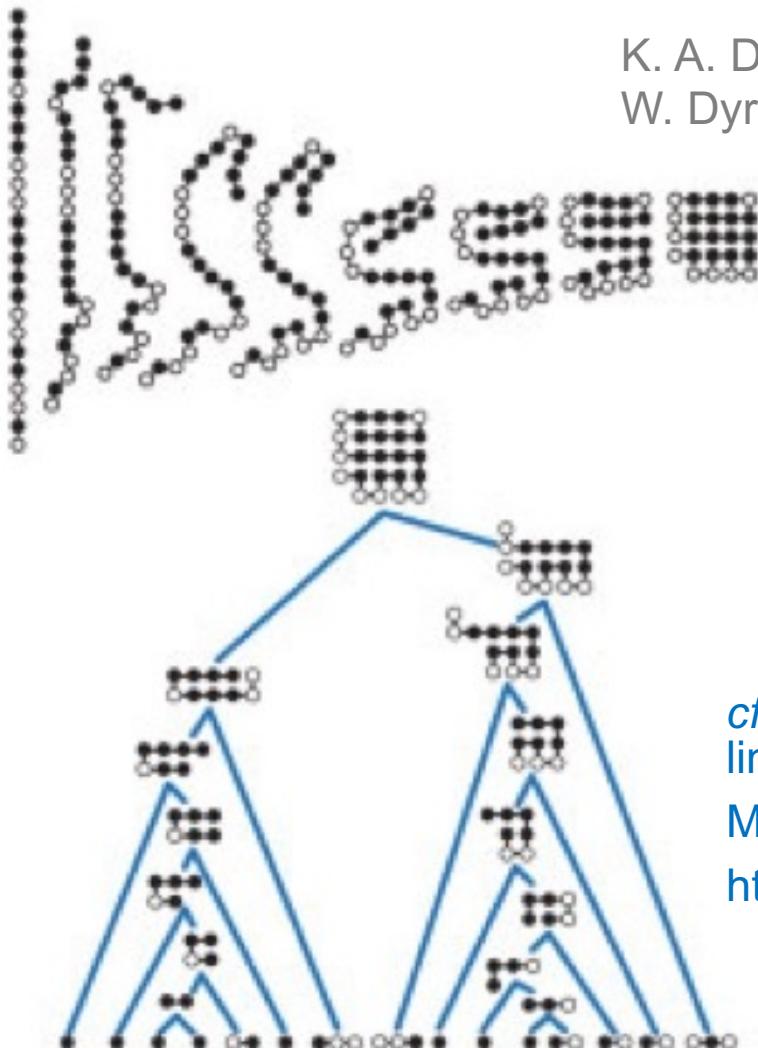
S. B. Ozkan *et al.*, PNAS 104, 11987 ('07)

Parsing Protein-Folding Routes

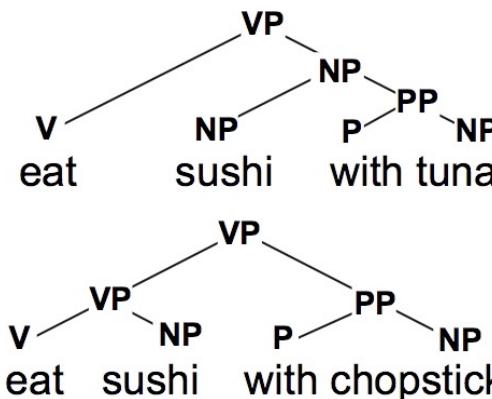
Computational linguistics

(1) Formal grammar to describe protein-folding routes

(2) Dynamic programming for an efficient algorithm for the folding routes



K. A. Dill et al., *Polymer* **48**, 4289 ('07)
W. Dyrka et al., *Alg. Mol. Biol.* **8**, 31 ('13)



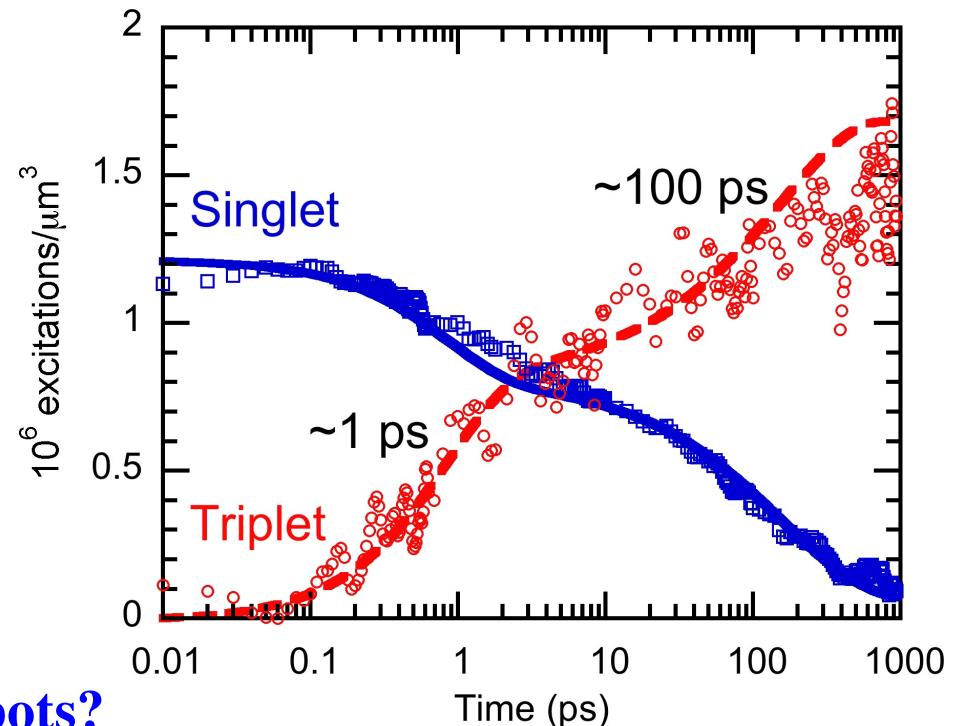
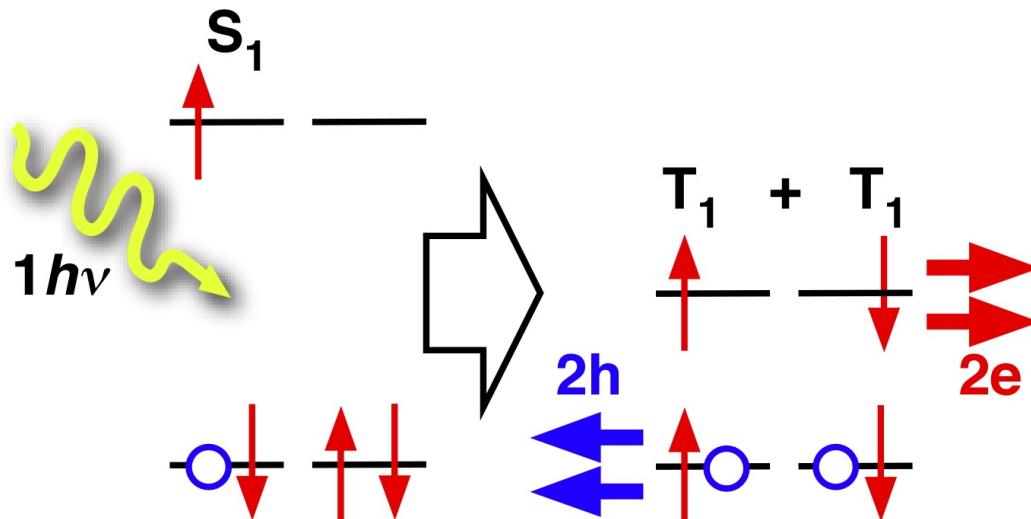
eat sushi with tuna
eat sushi with chopsticks

cf. Mathematical equivalence between generative linguistics & renormalization in physics

Matilde Marcolli, Noam Chomsky, Robert Berwick
<https://arxiv.org/abs/2305.18278>

Singlet Fission in Amorphous DPT

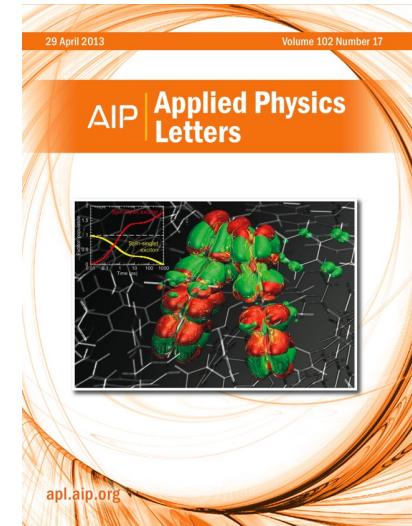
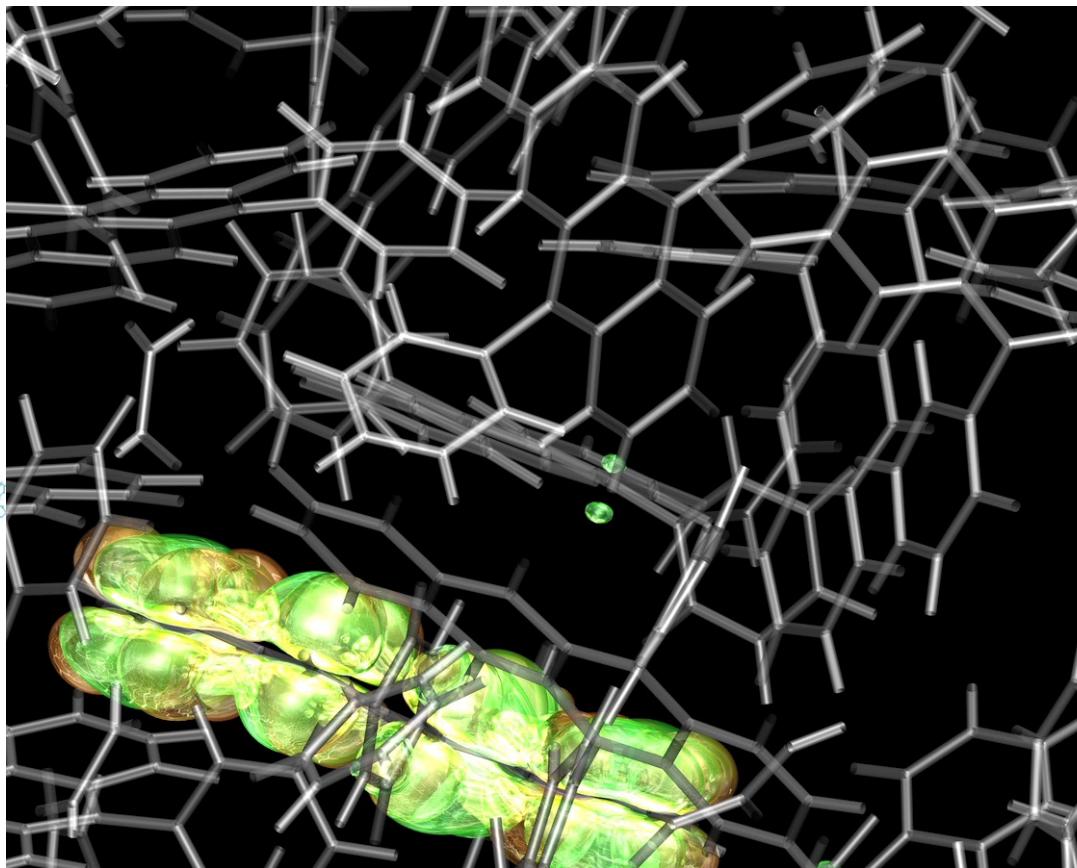
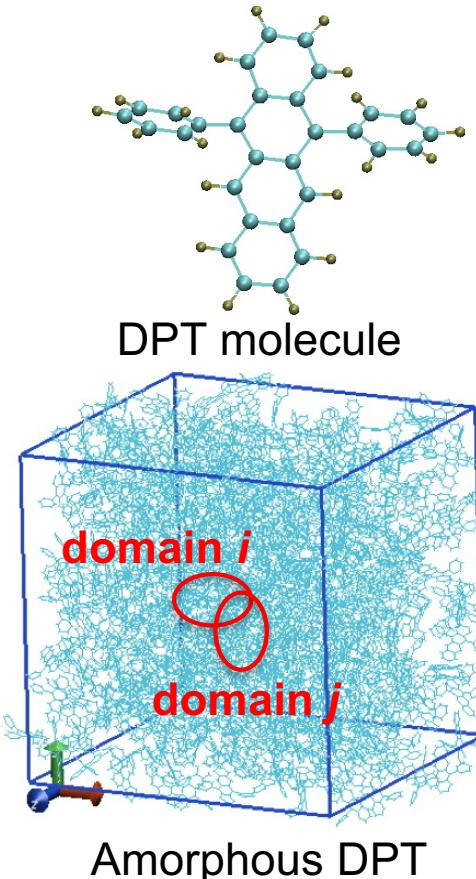
- Photo-current doubling by splitting a singlet exciton into 2 triplet excitons
- Singlet fission (SF) in mass-produced disordered organic solid
→ efficient low-cost solar cells
- Exp'l breakthrough: SF found in amorphous diphenyl tetracene (DPT)
- Ultrafast transient absorption measurements identified *two time-scales* (1 & 100 ps) for exciton population dynamics
- Hypothesis: Existence of *SF hot spots* S. T. Roberts *et al.*, JACS 134, 6388 ('12)



- Problem: *Molecular origin of SF hot spots?*

Divide-Conquer-Recombine KMC

- Move up from molecules to microstructures
- Challenge: Unprecedented 10^4 -atom NAQMD simulation
- Computational approach: Divide-conquer-recombine (DCR) NAQMD



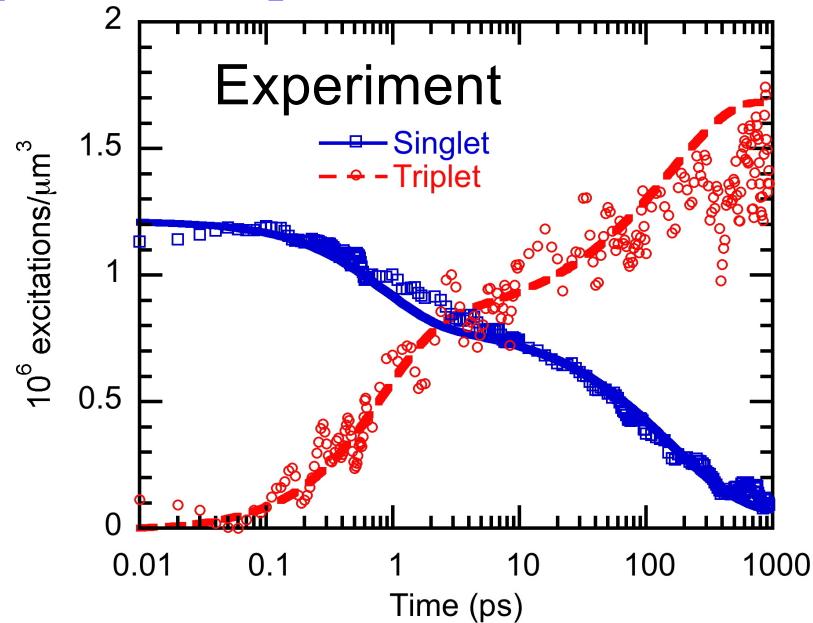
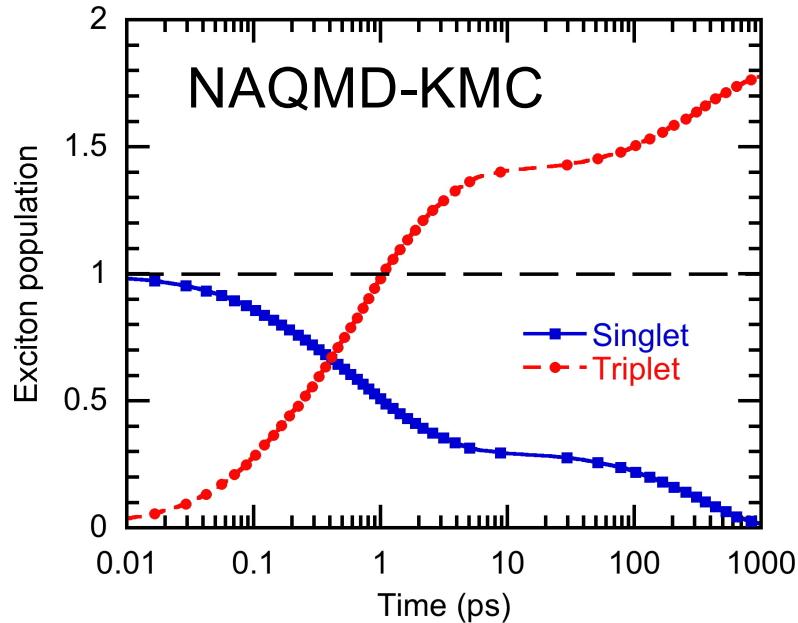
Quasi-electron
Quasi-hole

- **DCR-NAQMD (phonon-assisted exciton dynamics) + time-dependent perturbation theory (singlet-fission rate) + kinetic Monte Carlo calculations of exciton population dynamics in 6,400-atom amorphous DPT**

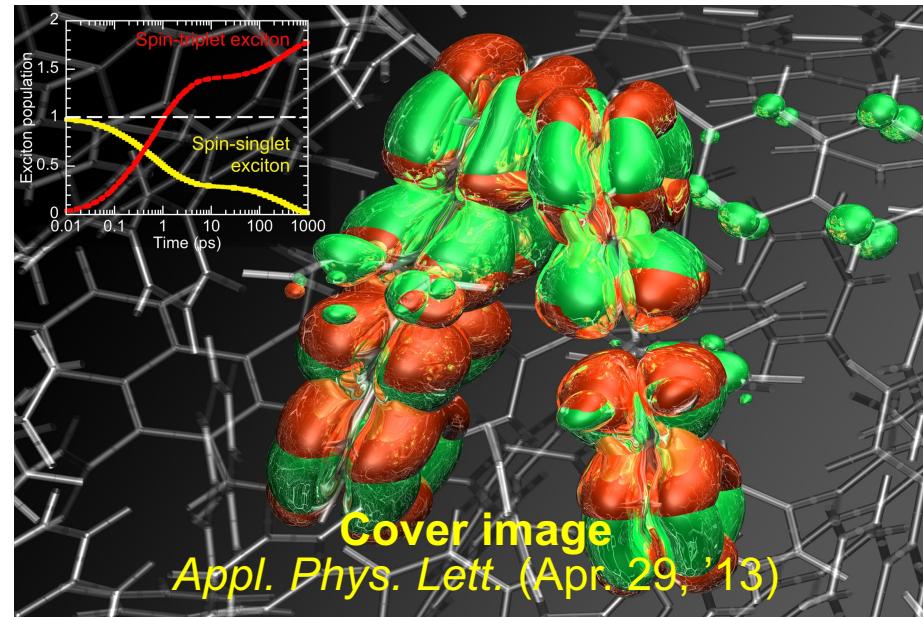
F. Shimojo *et al.*, *J. Chem. Phys.* **140**, 18A529 ('14)

NAQMD-informed Kinetic Monte Carlo

- NAQMD-KMC exciton population dynamics reproduces the experimentally observed two time scales (~ 1 & 100 ps) in amorphous DPT



W. Mou *et al.*,
APL 102, 173301 ('13)



S. T. Roberts *et al.*,
JACS 134, 6388 ('12)