

Determining sequence-dependent DNA oligonucleotide hybridization and dehybridization mechanisms using coarse-grained molecular simulation, Markov state models, and infrared spectroscopy

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Abstract

A robust understanding of the sequence-dependent thermodynamics of DNA hybridization has enabled rapid advances in DNA nanotechnology. A fundamental understanding of the sequence-dependent kinetics and mechanisms of hybridization and dehybridization remains comparatively underdeveloped. In this work, we establish new understanding of the sequence-dependent hybridization/dehybridization kinetics and mechanism within a family of self-complementary pairs of 10-mer DNA oligomers by integrating coarse-grained molecular simulation, machine learning of the slow dynamical pathways, data-driven inference of long-time kinetic models, and experimental temperature-jump infrared spectroscopy. For a repetitive ATATATATAT sequence, we resolve a rugged dynamical landscape comprising multiple metastable states, numerous competing hybridization/dehybridization pathways, and a spectrum of dynamical relaxations. Introduction of a G:C pair at the terminus (GATATATATC) or center (ATATGCATAT) of the sequence reduces the ruggedness of the dynamics landscape by eliminating a number of metastable states and reducing the number of competing dynamical pathways. Only by introducing a G:C pair midway between the terminus and the center to maximally disrupt the repetitive nature of the sequence (ATGATATCAT) do we recover a canonical two-state model of hybridization/dehybridization over a smooth landscape with no intermediate metastable states. Our results establish new understanding of the dynamical richness of sequence-dependent kinetics and mechanisms of DNA hybridization/dehybridization, present a molecular basis with which to understand experimental temperature jump data, and furnish foundational design rules by which to rationally engineer the kinetics and pathways of DNA association and dissociation in burgeoning DNA nanotechnology applications.

1 Introduction

Over the last couple of decades, DNA has proven to be much more than a vessel for genetic information. From sensing to computing to directed self-assembly, the programmable and predictable nature of DNA has unlocked numerous unforeseen nanotechnology applications.^{1–4} Recently, single molecule localization techniques have exploited the rapid and transient binding of short DNA oligomers in order to achieve super-resolution microscopy and optical multiplexing.^{5–7} Predictive understanding of the sequence-dependent thermodynamics of DNA hybridization/dehybridization – the assembly/disassembly of a DNA duplex from two single strands – has underpinned the rational design of DNA oligomer sequences for nanotechnological applications, where sequence-dependent nearest-neighbor models can accurately account for mismatched pairs, dangling ends, and other non-native bonding effects.^{8,9} Secondary DNA structures such as hairpins and G-quadruplexes have also been studied in depth and leveraged for nanotechnology applications.^{10–12} Predictive models of the *dynamical*, as opposed to purely thermodynamical, behaviors of DNA have become increasingly important in developing technologies such as DNA-PAINT (DNA Points Accumulation For Imaging In Nanoscale Topography), but developments in dynamic DNA nanotechnologies have outpaced our understanding of the dynamics themselves.^{13–15} Many experimental and computational studies have investigated DNA dynamical phenomena from the picosecond to millisecond range.^{16–20} Kinetic models have been developed for particular DNA processes such as toehold exchanges and optical barcoding^{21,22} and supervised machine learning techniques have been combined with experimental measurements to predict the on/off rates as a function of sequence.^{6,23,24} A comprehensive understanding of the full dynamical landscape of hybridization/dehybridization accounting for the sequence-dependent metastable states and association/dissociation pathways remains lacking and fundamental questions remain unresolved. For example, it remains unclear the extent to which hybridization of short DNA oligomers largely proceeds in a conventionally assumed “all-or-nothing” fashion or if long-lived metastable states facilitate the transition.^{17,19,25–28} Out-of-register “shifted” base paired

structures^{17,25,29,30} and frayed structures^{31–34} stand as candidates for metastable states with the potential to mediate substantial deviations from all-or-nothing behavior, but the extent to which these states are kinetically relevant is difficult to determine experimentally and is likely to be highly sequence-dependent. The development of predictive models and design rules with which to engineer DNA strands with tailored hybridization/dehybridization kinetics and pathways is vital to advancing rational design of DNA strands for nanotechnology applications and is also of importance in understanding fundamental biological processes such as transcription and gene regulation.

Our understanding of hybridization dynamics has been built from decades of experiments – such as temperature-jump, salt-jump, pH-jump, and other perturbative methods – that rapidly stimulate DNA and monitor relaxation to a new equilibrium.^{28,35–41} More recently, single molecule diffusion and tethered multifluorophore assays have facilitated equilibrium analysis, but these results can be hampered by slow data collection rates and fluorescent tags effects on strand dynamics, particularly for shorter oligomers.^{23,42–44} A number of computational modeling approaches have also been employed to provide molecular-level resolution of hybridization. Simplified lattice models can recapitulate the essential aspects of the hybridization pathways but lack the realism of continuous space representations^{25,45}. The long time scales associated with hybridization/dehybridization events place them outside the reach of unbiased all-atom molecular dynamics simulations,²⁹ but they can be observed by employing enhanced sampling techniques such as metadynamics, umbrella sampling, transition path sampling, and forward flux sampling,^{18,46–53} or by using elevated temperature or denaturing solvent concentrations to induce one-way dissociation events.^{54,55} The effect of the applied bias upon the thermodynamics can be rigorously corrected for using standard reweighting techniques, but approaches to rigorously correct the kinetics, particularly under the conditions of high bias necessary for good sampling, are in their infancy.^{56–61} A number of coarse-grained DNA force fields have been developed that enable direct observation of these events over microsecond time scales via unbiased coarse-grained molecular dynamics

(CGMD) simulations,^{30,48,53,62,63} which, up to a speedup factor associated with the smoothing of the underlying free energy landscape inherent to the coarse-graining procedure, can preserve a faithful model of the unbiased dynamics and associated pathways. These models have previously been used to study biological phenomena such as nucleosome dynamics^{64,65} and transcription factor binding^{66,67} as well as nanotechnology applications such as strand displacement^{68,69} and DNA origami^{70,71}.

In this work, we study a family of self-complementary pairs of 10-mer DNA oligomers using coarse-grained molecular simulation, machine learning, and data-driven inference of long-time kinetic models to establish new understanding of the influence of sequence upon hybridization/dehybridization kinetics and mechanisms. This family of oligomers – 5'-ATATATATAT-3' (AT-all), 5'-GATATATATC-3' (GC-end), 5'-ATATGCATAT-3' (GC-core), and 5'-ATGATATCAT-3' (GC-mix) – was designed to probe the influence of the placement of a G:C pair within an otherwise repetitive A:T sequence and has been the subject of our prior experimental investigations using temperature-jump infrared spectroscopy and simple lattice models.¹⁹ We validate the new computational models of hybridization/dehybridization dynamics developed in this work against new and existing experimental data and reinterpret our prior experimental observations in light of the new computational understanding. Consistent with previous studies,^{25,29,53} we find the degree of repetitiveness in the sequence – and therefore the kinetic accessibility and thermodynamic stability of non-native states – leads to richer dynamics populated by a diversity of long-lived metastable states. Our data-driven modeling and analysis rigorously quantifies these behaviors and furnishes accurate predictive models of the hybridization/dehybridization rates, dynamical pathways, and metastable states. Specifically, we demonstrate that disrupting repetitive stretches of A:T bases by placement of interrupting G:C base pairs enables us to tune the landscape from rich six-state to simple two-state “all-or-nothing” behavior, and the specific location of the interrupting pair can be used to modulate the stability of long-lived frayed states that facilitate the hybridization/dehybridization process. Analysis of the configurational ensemble within

each metastable state reveals the conformational heterogeneity and dynamical interconversions proceeding on time scales that lie below those resolvable within the long-time kinetic model. Taken together, our analyses establish new molecular-level understanding of the sequence-dependent kinetics and pathways through quantitative predictive models for the long-time system dynamics, resolution of the dynamical folding pathways and metastable states, and elementary design rules with which to sculpt and qualitatively alter the dynamical behaviors of the system. We anticipate that this new foundational understanding, and the extension of our approach to more extensive families of DNA sequences, can guide the rational design of DNA oligomers with tailored kinetic properties engineered for DNA nanotechnology applications such as DNA-PAINT.^{6,7}

2 Methods

2.1 Computational Methods

2.1.1 Molecular dynamics simulations

We performed molecular dynamics simulations of four 10-base self-complementary double-stranded DNA sequences that we have previously studied by ultra-fast temperature-jump infrared spectroscopy¹⁹: 5'-ATATATATAT-3' (AT-all), 5'-GATATATATC3-3' (GC-end), 5'-ATATGCATAT-3' (GC-core), and 5'-ATGATATCAT-3' (GC-mix). We modeled the DNA sequences using the coarse-grained 3-Site-Per-Nucleotide v2 (3SPN.2) that uses three spherical beads to represent the phosphate, deoxyribose sugar, and nitrogenous base of each nucleotide and employs anisotropic interaction potentials to accurately treat intra-strand base-stacking, inter-strand cross-stacking, and base pairing.⁴⁸ The model was parameterized against experimental data on bond lengths, bend angles, torsional angles, base step energies, and base stacking free energies, and reliably reproduces the structure, melting temperatures, persistence lengths, and sequence, salt, concentration, and temperature effects

on duplex formation.⁴⁸ The model enables access to millisecond time scales and has been widely-adopted to study numerous phenomenon including DNA packing in viral capsids, protein-DNA binding, and nucleosome unwrapping.^{64,72,73} Although the 3SPN.2 model was not directly parameterized against dynamical experimental data, we will show below that the predicted sequence-dependent kinetics and relaxation are, within a corrective scaling factor, in very good agreement with observed experimental trends.

All calculations were performed using the LAMMPS simulation package (<http://lammps.sandia.gov>) in accordance with best practices for the 3SPN.2 model.⁷⁴ A single pair of self-complementary sequences were placed in a cubic periodic box with side length 7.8 nm corresponding to a single-strand concentration of 7 mol/L. Solvent effects were modeled implicitly by employing Langevin dynamics^{75,76} with an experimentally motivated per-site friction coefficient of $\xi = 9.94 \times 10^{-11} \text{ m}^2/\text{s}$.^{48,77} We specified a 240 mM implicit salt concentration and treated electrostatic interactions using the Debye-Hückel with a 5 nm cutoff radius.⁷⁸ Simulations were performed in the NVT ensemble employing a Langevin thermostat.⁷⁹ Each sequence was simulated at its melting temperature – AT-all: 309 K, GC-end: 317 K, GC-core: 324 K, GC-mix: 324 K – in order to maximize the number of spontaneous transitions between dissociated and hybridized states. Melting temperatures for each sequence were determined empirically by comparing the ratio of hybridized to dissociated populations over a 10 K temperature ramp centered on the Nearest Neighbors model predicted melting temperature. The temperature at which the hybridized and dissociated populations were closest was selected. The Langevin equations of motion were integrated using the scheme of Bussi and Parrinello⁷⁶ with a 20 fs integration time step. We performed 40 independent simulations for each of the four sequences with half of the runs initialized from the hybridized state and half from the dissociated state. The initial hybridized state was defined following 3SPN.2 best practices using the crystal structure coordinates of Arnott et al.⁸⁰ The dissociated state was generated from the hybridized state by displacing one strand away from the other by 1 nm in each of the x , y , and z directions. The magnitude of this displacement did not affect

the results so long as all native WC bonds were completely broken. Initial bead velocities were assigned from a Maxwell-Boltzmann distribution at the temperature of interest. Each simulation was conducted for $26 \mu\text{s}$ and frame saved to disc every 100 ps, requiring ~ 24 CPU-hours on $28 \times$ Intel E5-2680v4 CPU cores. The first $1 \mu\text{s}$ of each run was discarded for equilibration providing us with $40 \times 25 \mu\text{s} = 1 \text{ ms}$ of simulation data for each sequence, during which time we observed 55-100 hybridization/dehybridization events.

2.1.2 Markov state model construction

Markov state models (MSMs) are a powerful approach to infer long-time kinetic models from short molecular simulation trajectories^{81 82-85} that we employ to construct high-resolution sequence-dependent kinetic models of DNA hybridization and dissociation. MSMs have recently been implemented to study the hybridization mechanism of one particular 14-mer DNA oligomer, but determining the sequence-dependent kinetics and mechanisms was not the focus of this study.⁸⁶ An energy disconnectivity graph-based approach was used to interrogate the differences in hybridization rates and mechanisms between GGGGGG and GCGCGC hexamers to reveal strong deviations from “all-or-nothing” behaviors and the importance of zippering and slithering mechanisms.¹⁷ Kinetic models were constructed not from the dynamical trajectories of the molecular model, but by estimating rate constants between local minima were estimated using a transition state theory approximation. Finally, a recent application of MSMs to the long-time dynamics of short RNA oligonucleotides revealed stacking time scales to be highly sequence dependent.⁸⁷ In this work, MSMs were constructed for each of the four DNA sequences from the $40 \times 25 \mu\text{s}$ simulation trajectories following the six-step protocol detailed in Ref.⁸⁸: (i) trajectory featurization, (ii) dimensionality reduction, (iii) microstate clustering and microstate transition matrix inference, (iv) macrostate clustering and macrostate transition matrix inference. Calculations were performed using the PyEMMA software package.⁸⁹

Featurization. Trajectories comprising the Cartesian coordinates of the DNA strands

as a function of time were featurized using the MDtraj Python libraries⁹⁰ to represent the system in a manner that exposes the essential system dynamics but eliminates trivial translation and rotational invariances. We adopt intermolecular pairwise distances $d(i, j)$ between the centers of mass of the 10 bases as a natural rototranslationally invariant featurization that represents each system configuration as the $10 \times 10 = 100$ -element vector of pairwise distances between all bases within the complementary pair of 10-base strands. One additional symmetry arises from the self-complementary nature of these sequences – the sense and anti-sense strands in each pair are identical – such that the representation of the system under our featurization should remain unchanged upon inverting the arbitrary labeling of strand “1” and strand “2”.⁸¹ The 100-element pairwise distance vector is not invariant to this permutation, but can easily be made so via a simple symmetrization operation in which each of the $\binom{10}{2} = 45$ intermolecular pairwise distances are replaced by the mean of the two permutationally invariant distances. Specifically, $(d(i_1, j_2) = d(i_2, j_1)) \leftarrow 0.5(d(i_1, j_2) + d(i_2, j_1))$, where i_1 denotes the i^{th} base on strand 1 and j_2 the j^{th} base on strand 2.⁸¹ Finally, we took the reciprocal of the permutationally-symmetrized pairwise distances to provide higher resolution and differentiation between proximate strand configurations in the near hybridized state compared to distantly separated dissociated strands. VAMP-2 scoring – calculation of the sum of the squared estimated eigenvalues of the transfer operator – of trajectories under a particular featurization provides a measure of the kinetic variance carried by that featurization.^{91–94} Performing VAMP-2 scoring at a lag time of $\tau = 1.2$ ns and retaining the top five modes, reveals that the reciprocal permutationally-symmetrized pairwise distances can carry up to twice the kinetic variance as the non-reciprocal distances, suggesting that the higher resolution offered at close intermolecular distances can indeed boost the dynamical representational power of the model. Somewhat surprisingly, we observed that augmenting our set of intermolecular distances with intramolecular distances led to no improvement of the VAMP-2 score, indicating that the kinetically-relevant conformational state of the two strands are adequately represented via the intermolecular distances and leading us to employ

only intermolecular distances within our featurization.

Dimensionality reduction. The featurized trajectories were then projected into a low-dimensional space in preparation for microstate clustering. The standard approach to doing so is to employ time-lagged independent components analysis (tICA) to learn a linear projection into a low-dimensional embedding that maximally preserves the kinetic variance in the data.^{92,95,96} In this work, we instead employ state-free reversible VAMPnets (SRVs) that can be conceived of as a nonlinear version of tICA.⁹⁷ SRVs employ neural networks to learn flexible nonlinear functions of the trajectory featurization that better approximate the slow dynamical modes of the system and have been shown to produce substantially higher resolution MSMs than those developed using tICA in applications to WW-domain and Trp-cage mini-proteins.^{88,97} Importantly, the SRV modes were learned independently for each system to best approximate the slow collective modes for that particular DNA sequence. SRVs were trained using the SRV package we previously developed (<https://github.com/hsidky/srv>) employing the default network architecture of two hidden layers each comprising 100 neurons and tanh activation functions, a learning rate of 0.001, and a batch size of 50,000. We adopted a lag time of $\tau = 1.2$ ns as appropriate short to resolve the dynamical details of the hybridization/dehybridization dynamics.⁹⁸ As observed by Husic and Pande, it is conceptually incorrect to treat the lag time as a model hyperparameter to be self-consistently optimized via the VAMP-2 score, but rather as a physically-motivated choice designed to expose the dynamical motions relevant at a particular time and length scale of interest.⁹⁹ As we shall show, this choice of lag time leads to converged and Markovian macrostate MSMs. We guarded against overfitting using five-fold cross-validation in which we divided the trajectory data into 50:50 training:validation splits. We observed plateau of the validation loss and no evidence of overfitting after 20 epochs of training for each system that required approximately 22 GPU-minutes on a single NVIDIA Tesla K80 GPU card. A VAMP-2 scoring of the cumulative kinetic variance explained as a function of number of SRV collective modes retained also showed no evidence of overfitting – as would be evinced by

separation of the training and validation VAMP-2 scores⁸⁸ – and exhibited a knee for each of the four DNA sequences after the fifth, fourth, third, and second slow modes for AT-all, GC-end, GC-core, and GC-mix, respectively (Fig. S1 in the Supporting Information), and motivating the construction of 5D, 4D, 3D, and 3D embeddings, respectively.

Microstate clustering. The SRV projections of the 10 million frames recorded over the course of the 1 ms MD trajectories collected for each DNA sequence were then clustered into microstates using k-means clustering. The VAMP-2 score of the microstate transition matrix constructed for each sequence at the selected $\tau = 1.2$ ns was insensitive to the choice of the number of microstates over the range 100-1000, motivating our selection of 200 microstate clusters for each system.

Macrostate clustering. The 200 microstates comprising each system were finally coarsened into our terminal macrostate MSM. The microstate transition matrix for each system was computed at a range of lag times τ and then diagonalized to recover the corresponding eigenvalues λ_i and associated implied time scales $t_i = -\tau / \ln |\lambda_i|$.⁸⁵ The implied time scale plots for the four DNA sequences are presented in Fig. S2. We observe rapid convergence of the implied time scales t_i with lag time τ for all systems, motivating the construction of high resolution macrostate MSMs at a lag time $\tau = 1.2$ ns. For this choice of lag time, we recover 5, 4, 2, and 1 implied time scales for the AT-all, GC-end, GC-core, and GC-mid systems, respectively. The identification of $(i - 1)$ implied time scales implies the presence of $(i - 1)$ slow modes and motivates the coarsening of the system into i macrostates. We estimate these i macrostates by applying PCCA+ spectral clustering to the leading $(i - 1)$ eigenvectors of the microstate transition matrix.^{100–102} We then estimate the corresponding 6, 5, 3, and 2 macrostate transition matrices \mathbf{P} for the AT-all, GC-end, GC-core, and GC-mid systems, respectively, by projecting the MD simulation trajectories into these discrete macrostates. These macrostate MSMs constitute our terminal kinetic models. We validate the Markovian nature of the four MSMs by subjecting them to the Chapman-Kolmogorov (CK) test^{85,103,104}. This test asserts that the transition matrix for a Markovian (i.e., memo-

ryless) MSM constructed at a lag time τ should satisfy the condition $\mathbf{P}(k\tau) = \mathbf{P}^k(\tau)$, which states that k successive applications of the transition matrix constructed at a lag time τ should be equivalent to a single application of the transition matrix constructed at a lag time $k\tau$. We present in Fig. S3 the CK tests for each DNA sequence to demonstrate that the $\tau = 1.2$ ns models perform very well in predicting transition probabilities out to $k\tau = 7.2$ ns, validating the Markovian nature and kinetic validity of the four models.

2.2 Experimental Methods

2.2.1 Sample Preparation

Each DNA oligonucleotide was purchased from Integrated DNA Technologies (IDT) at desalt grade purity. Oligonucleotides were purified with 3 kD cutoff centrifugal filters (Amicon). All labile protons were exchanged in deuterium oxide (D_2O , Cambridge Isotopes, 99.9%). Oligonucleotides were prepared at a total strand concentration of 2 mM in 50 mM pD 7.2 sodium phosphate buffer with 240 mM NaCl and 18 mM $MgCl_2$. Prior to each measurement, DNA solutions were placed in a water bath at 90° C for 3 minutes and then cooled to room temperature under ambient conditions.

2.2.2 T-Jump IR Spectroscopy

The details of the technique and processing used to acquire temperature-jump infrared (T-jump IR) data have been described previously.^{105–107} Briefly, heating was initiated through optical excitation of the O-D stretch overtone transition of D_2O . The 1.98 μm pulses (5 ns, 20 mJ, 20 Hz) used for heating were generated from the frequency-doubled output of a Nd:YAG (YG 980, Quantel) later sent through an optical parametric oscillator (OPO). Nonlinear IR spectra are collected from 5 ns to 50 ms delays after the T-jump. T-jump heterodyne-detected vibrational echo (t-HDVE) IR spectra were acquired with Fourier transform spectral interferometry,¹⁰⁶ where the delay between the local oscillator (LO) and DVE signal was scanned in 5 fs steps between (-10) and 10 fs. t-HDVE spectra were acquired with a parallel

pulse polarization scheme. Data are presented using the recovered T-jump dispersed pump-probe (t-DPP) spectrum. t-DPP data are reported as the difference spectra with the 49 or 50 ms spectrum, which corresponds the initial temperature spectrum.

The sample was placed between two 1 mm thick CaF₂ windows separated by a 50 μm Teflon spacer enclosed in a home-built brass jacket. The initial temperature of the sample was set using a recirculating chiller connected to the brass sample jacket. The T-jump temperature change (ΔT) was set to 15 °C for all measurements and monitored using the change in transmission of the D₂O bend-libration combination band measured in the LO beam. The temperature change was quantified by comparing the change in transmission of the LO beam with a FTIR temperature series of D₂O.

2.2.3 Determination of Fast and Slow Dissociation Rates

To determine observed rates from the T-jump data, the time-domain t-HDVE data was inverse Laplace transformed into the rate domain using a maximum entropy approach (MEM-ILT).¹⁰⁸ Observed rates were computed from the amplitude-weighted mean rate across detected IR frequency, as previously described.²⁸ The fast response k_d^{fast} is defined purely as this amplitude-weighted mean rate, whereas the dissociation rate constant k_d^{slow} was extracted from the observed rate of the slow response λ^{slow} using a two-state model for self-complementary oligomers,¹⁰⁹

$$\lambda^{\text{slow}} = k_d^{\text{slow}} + 4[S]_{T_f} k_a^{\text{slow}}, \quad (1)$$

where $[S]_{T_f}$ is the concentration of single-strand oligomer at the final temperature of the T-jump, and k_a^{slow} is the association rate constant. [[I renamed k_a as k_a^{slow} for consistency. Is this OK?]] In practice, Eqn. 1 is recast in terms of the dissociation equilibrium constant $K_d = k_d^{\text{slow}}/k_a^{\text{slow}}$,

$$k_d^{\text{slow}} = \frac{\lambda^{\text{slow}} K_d}{K_d + 4[S]_{T_f}}. \quad (2)$$

We use this expression to estimate k_d^{slow} , where we estimate K_d by ..., λ^{slow} by ..., and $[S]_{T_f}$ by ... [[What was written seems incomplete – it seems like we need to say how we estimate (i) λ^{slow} , (ii) K_d , and (iii) $[S]_{T_f}$, not k_d^{slow} and $[S]_{T_f}$? Am I understanding Eqn. 2 correctly?]] k_d^{slow} and $[S]_{T_f}$ come from melting curves measured with FTIR spectroscopy that are fit to a two-state all-or-nothing dissociation model.¹¹⁰ We used the FTIR melting curves previously reported in Ref.¹⁹

3 Results

3.1 Sequence-dependent coarse-grained kinetics recapitulate T-jump IR measurements

We first sought to demonstrate that the coarse-grained 3SPN.2 model accurately recapitulates the experimentally observed kinetics of DNA oligomer hybridization/dissociation by validating our computational predictions against temperature-jump infrared (T-jump IR) experiments. We conducted T-jump IR experiments for each DNA sequence as a function of temperature and extracted the “slow” k_d^{slow} (10-30 μs) and “fast” k_d^{fast} (70-100 ns) rates estimated from the T-jump response. The slow response has previously been attributed to duplex dissociation on microsecond time scales induced by the rapid heating of the initially hybridized duplex.^{19,28} The fast response is has been assigned to terminal base pair fraying,^{19,28} with this process corresponding to a relatively complex dynamical process that can span time scales from picoseconds to microseconds.^{32–34,111} All-atom simulations suggest that frayed ends can assume misaligned Watson-Crick bonds, base-sugar hydrogen bonds, and terminal stacked conformations.^{31,112}

To computationally mimic the T-jump process in our 3SPN.2 simulations, we conducted 1 μs simulations of an initially hybridized DNA duplex over a range of temperatures and monitored its structural relaxation. We performed 120 independent simulations for each DNA sequence at each temperature, and from these extracted computational estimates of

k_d^{slow} and fast k_d^{fast} (Fig. S4). First, we tracked the slow response corresponding to duplex dissociation in our simulations by compiling the distribution of times at which **both OR either** [[Pick the right word.]] of the central base pairs first separate to a distance of 1.3 nm. This cutoff was selected as the distance beyond with the strands are effectively non-interacting and defines the dissociated state. We extracted our computational estimate of k_d^{slow} by fitting a decaying exponential to the fraction of hybridized sequences as a function of time $f_{\text{hybridized}}(t) = \exp(-k_d^{\text{slow}}t)$. Second, we tracked the fast response corresponding to terminal base pair fraying by compiling the distribution of times at which either of the terminal base pairs first separated to a distance of 1.3 nm, corresponding to a complete breakage of the Watson-Crick (WC) interaction. We extracted our computational estimate of k_d^{fast} through a decaying exponential fit to the fraction of unfrayed sequences as a function of time $f_{\text{unfrayed}}(t) = \exp(-k_d^{\text{fast}}t)$.

We present in Fig. 1 a comparison of k_d^{slow} and k_d^{fast} estimated by computation and experiment. Although the 3SPN.2 model was not directly fitted against kinetic data,⁴⁸ its predictions of sequence dependent T-jump relaxation rates are, within a systematic scaling factor in time and systematic shift in temperature, in good agreement with observed experimental trends. It is well-known that the smoothing of the underlying free energy landscape induced by coarse-graining artificially accelerates the kinetics of coarse-grained molecular simulations and that different degrees of freedom may be accelerated by different factors.^{113–115} We find that the simulated slow responses corresponding to center-of-mass translation of the strands during dissociation of the duplex is $\sim 10\times$ accelerated relative to experiment, whereas the fast responses corresponding to fraying of the terminal bases is $\sim 120\times$ accelerated. We apply these sequence-independent scaling factors to our reported computational values. Although the 3SPN.2 model reproduces melting temperatures relatively well, we observed a systematic 4 K under-prediction in making the experimental comparison and so we apply a universal (+4) K corrective calibration to our computational results. We note that these empirical calibration factors to the 3SPN.2 predictions are applied only for the purposes of making

an experimental comparison. The computational time scales and melting temperatures reported in the remainder of the paper are not corrected since we are only interested in the relative trends in the behaviors of the four sequences.

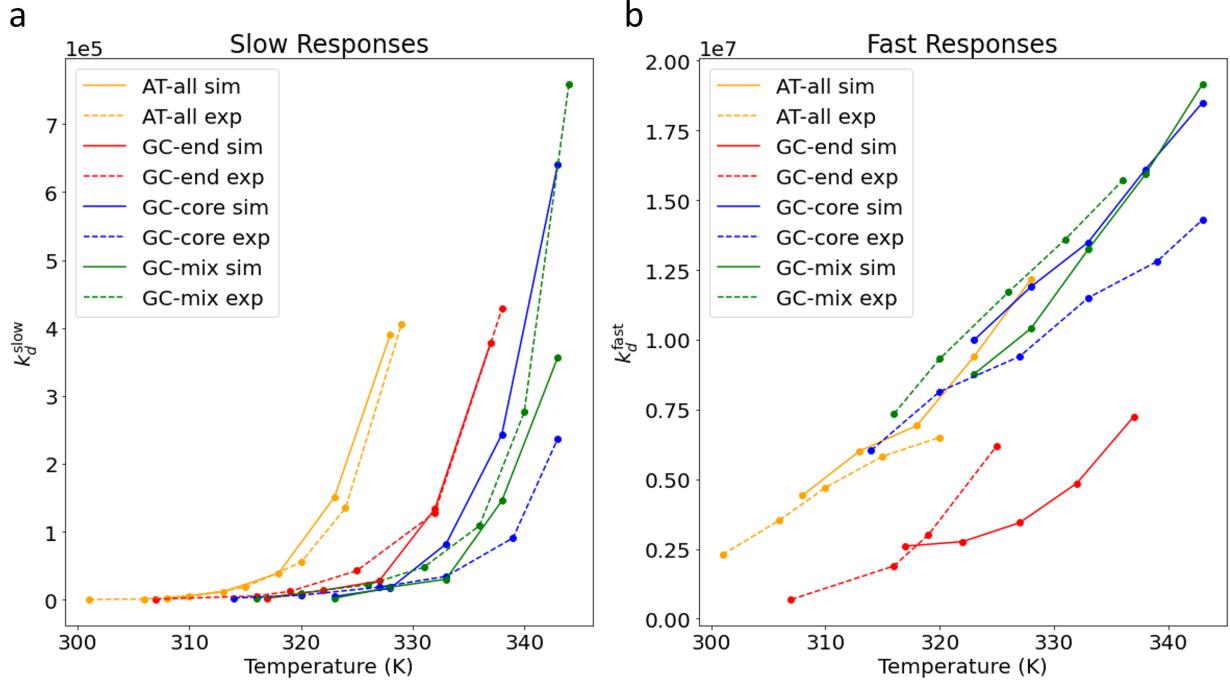


Figure 1: Experimental measurements and computational predictions of slow and fast at T-jump IR responses. Results are reported in terms of the final T-jump temperature. (a) The experimental and simulated slow rate constants k_d^{slow} corresponding to duplex dissociation over long time scales. (b) The experimental and simulated fast rate constant k_d^{fast} corresponding to terminal base-pair fraying on short time scales. The simulation results are corrected by a sequence-independent scaling factor that corrects for a $10\times$ acceleration of the slow dissociation dynamics and $120\times$ acceleration of the fast fraying dynamics. The simulated temperature in all cases is subjected to a (+4) K corrective calibration to account for an observed systematic under-prediction of the melting temperature by the 3SPN.2 model

In Fig. 1a we report an exponential increase of k_d^{slow} with temperature, as expected from the large enthalpic barrier to duplex dissociation.^{20,37,39} Under the time and temperature calibration corrections, we see generally very good agreement between the computational and experimental curves. The computational rates do tend to systematically under-predict the experimental values at low temperatures, an effect that we ascribe to the fact that the experimental T-jump responses likely contain a mixture of dissociation and hybridization

events – the latter of which persist to lower temperatures than the former – whereas the computational analysis considers dissociation alone. Of the four sequences, GC-core shows the largest discrepancy between computation and experiment, although the general trends exponential trend is preserved. This may be a result of its high propensity to fray (cf. Section 3.5). In Fig. 1b we expose a largely linear dependence of k_d^{fast} upon temperature for AT-all, GC-end, and GC-mix compared to an exponential dependence for GC-end. This can be understood via the comparatively larger enthalpic barrier for dissociation of the terminal G:C base pair in GC-end compared to that for the A:T terminal pair in the other three sequences. Again we see good agreement between the scaled computational predictions and the experimental T-jump measurements. The favorable comparison of computation and experiment provides support for the capacity of the 3SPN.2 model to reliably reproduce sequence-dependent trends in the slow and fast kinetics of the four DNA oligomers.

3.2 SRV-MSMs for each sequence

We now proceeded to construct Markov state models (MSMs) from 1 ms of aggregated simulation trajectories for each of the four sequences at their respective melting temperatures to generate sequence-dependent kinetic models. MSMs are extremely valuable in providing both a quantitative predictive model and a physically comprehensible mechanistic understanding of the long-time dynamical evolution of the system between an ensemble of metastable macrostates. We present in Fig. 2 the inferred MSMs for each of the four 10-base DNA sequences. Across all four sequences we identify a totality of seven metastable macrostates corresponding to the fully hybridized state (H) in which all native base pairings are intact, four shifted states in which the strands are translated out-of-register by two or four bases in the 5' (5S2, 5S4) or 3' (3S2, 3S4) direction, a frayed state (F4) – unique to GC-core – in which the four terminal A:T base pairs are unbound, and the fully dissociated state (D). We present these seven macrostates in Fig. 2a along with schematic and cartoon renderings of representative microstates contained within each of these macrostates. In Fig. 2b we

present the occupancy probabilities of each state at thermodynamic equilibrium. By virtue of the fact that each sequence is simulated at its corresponding melting temperature (T_m), the probability of the dissociated state (D) is, by construction, approximately equal to the sum of the probabilities over the remaining six states (H, 5S2, 3S2, 5S4, 3S4, F). In Fig. 2c we present a visualization of the macrostate MSMs for each of the four sequences showing the connectivity between the identified macrostates. The macrostates are represented as orange circles in proportion to their equilibrium probabilities and the grey arrows indicate the probability of hopping from one macrostate to another under one time step of the kinetic model. The fluxes between the macrostates provide a wealth of high-level, interpretable information on the sequence-dependent metastable states and hybridization/dehybridization pathways. Immediately we identify that the AT-all sequence possesses a rich and complex dynamical landscape comprising six metastable states whereas GC-mix exhibits far simpler two-state “all-or-nothing” behavior. In Fig. 2d we present the so-called implied time scales of each MSM. These time scales correspond to the relaxation times of the DNA dimer among its constituent metastable macrostates. The leading implied time scale for each system corresponds to the characteristic time scale for hybridization/dehybridization. Since each system is simulated at the same concentration and at its respective melting temperature, it is not surprising that the leading time scale is approximately equal for all four systems and corresponds to the characteristic time scale for hybridization/dehybridization. The spectrum of higher order time scales corresponds to increasingly quicker relaxations between the metastable macrostates within the kinetic model and resolve the interesting sequence-dependent differences in the hybridization/dehybridization kinetic pathways. The total number of implied time scales is typically one fewer than the number of metastable macrostates and the existence of large implied time scales is indicative of slowly relaxing kinetic processes. The dense spectrum of slow implied time scales for AT-all is indicative of its relatively complex kinetic landscape whereas that for the two-state GC-mix comprises only a single time scale corresponding to hybridization/dehybridization. We now proceed to

analyze in detail the sequence-dependent thermodynamics, kinetic, and mechanisms exposed by the four MSMs.

[[In the caption to Figure 2: (i) Change panel labels to lower case. (ii) Improve resolution of images. (iii) Label the MSMs in panel c as you did for the bar charts in panel b; AT-all, GC-end, etc. (iv) You nicely label panel a “Macrostates”. Can you also label the other panels following the labels I have suggested in the caption?]]

3.3 Comparison of MSM thermodynamic predictions with NN model

We first compare the thermodynamic predictions for the equilibrium macrostate probabilities to those of predictive sequence-dependent models for the thermodynamics of DNA association. The nearest neighbor (NN) model is popular model of DNA hybridization thermodynamics that predicts the free energy of duplex formation as a sum over helix initiation terms and the hybridization free energies of nearest neighbor pairs of bases that account for both the specific WC pairings and the modulating effects of the local (i.e., nearest neighbor) environment.^{8,9} The parameters of the NN model were estimated by regressing over 108 experimental measurements to furnish a predictive model for the free energy of association as a function of DNA sequence and explicitly account for stacking contributions of native pairs, internal mismatches, and dangling ends. We apply the NN model to estimate the (relative) free energy F of each of the macrostates occupied by each of the four sequences. The free energy of each macrostate is related to its equilibrium occupancy probability P via the statistical mechanical relationship $F = -k_B T \ln P + C$, where T is temperature, k_B is Boltzmann’s constant, and C is an additive constant reflecting our ignorance of the absolute scale of free energies. Since the additive constant cancels out in the evaluation of relative free energies between macrostates, this calculation provides a means to compare the free energies predicted by our MSMs (Fig. 2) to those of the NN model. A full accounting of the application of the NN model to the macrostates occupied by each of the four sequences is provided in the [Supporting Information](#).

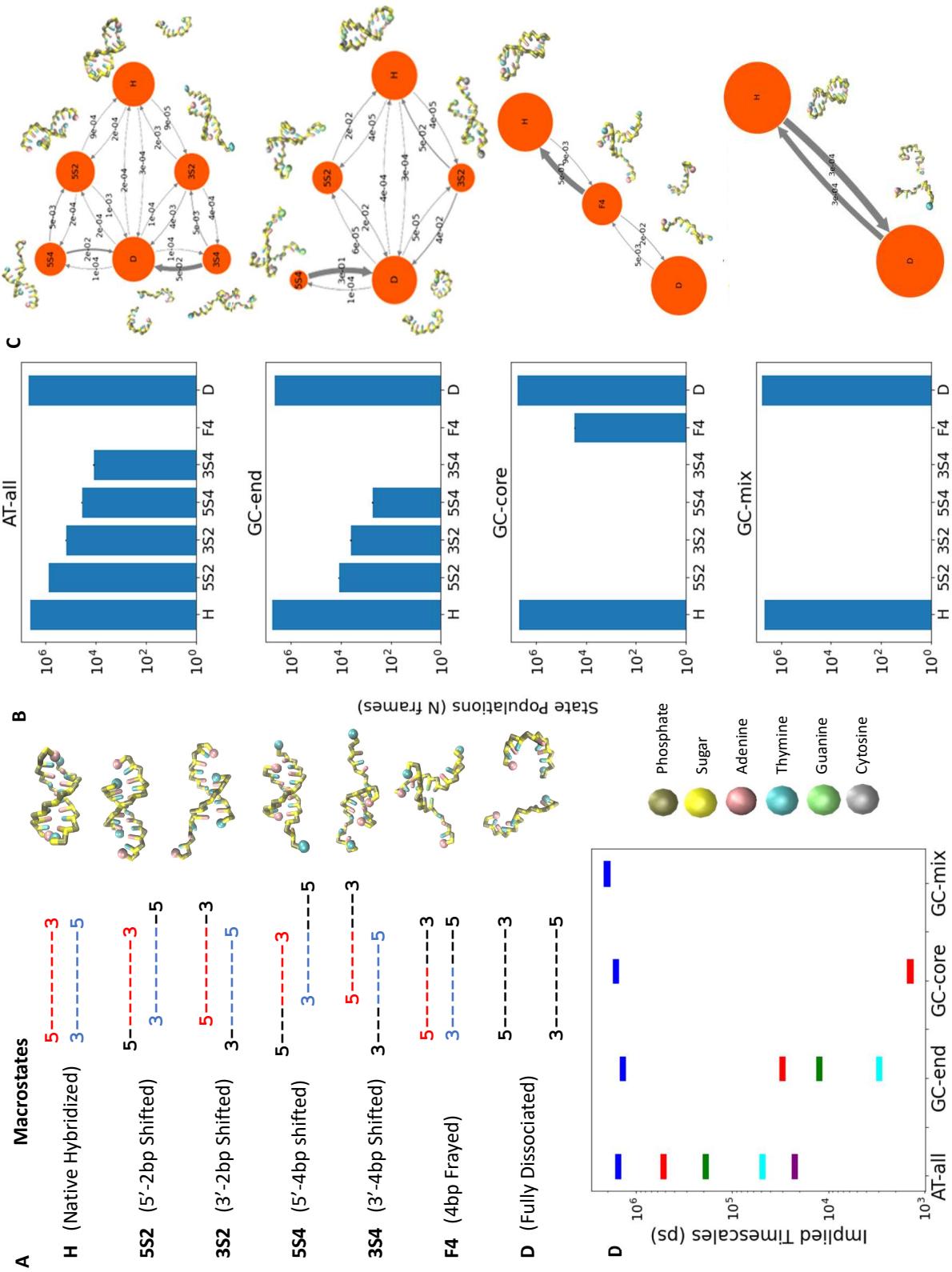


Figure 2: Thermodynamic and kinetic predictions of the sequence-specific MSMs for AT-all, GC-end, GC-core, and GC-mid. (a) **Macrostates.** Schematic representation of the seven metastable macrostates occupied by one or more of the four sequences: fully hybridized state (H), two-base out-of-register shifted states in the 5' (5S2) or 3' (3S2) direction, four-base out-of-register shifted states in the 5' (5S4) or 3' (3S4) direction, and the fully dissociated state (D). The line drawings represent the 10-base self-complementary sequences, where red-to-blue contacts indicates (possible) WC base pairing and black indicates an unbound bases. Adjacent to each line drawing we provide representative molecular structures corresponding to that macrostate. (b) **Thermodynamics.** Histograms reporting the number of the 10^7 total frames within the 1 ms simulation trajectories observed to occupy each of the seven macrostates, corresponding to our numerical estimates of the equilibrium occupancy probabilities. Uncertainties are calculated across 100 MSMs using a Bayesian MSM estimation are reported for each bar and are very small compared to the total counts. (c) **Kinetic networks.** MSMs illustrating the kinetic network for each sequence. The orange circles correspond to the macrostates occupied by each sequence and are labeled by the macrostate codes reported in panel a. The radii of the circles is proportional to the logarithm of the equilibrium occupancy probabilities reported in panel b. Molecular renderings of an illustrative snapshot from the coarse-grained molecular simulations are provided next to each macrostate. The grey arrows between macrostates indicate the presence of a kinetic flux between this pair of states at equilibrium and the arrow thickness is proportional to the flux. (To avoid congesting the diagram, arrows are not reported for fluxes lower than 3×10^{-6} [Units?].) The numerical value overlaid on each arrow reports the conditional probability that a system occupying the macrostate at the start of the arrow at time t will transition to the macrostate at the end of the arrow by time $(t + \tau)$, where $\tau = 1.2$ ns is the lag time corresponding to a single time step of the MSM. Large orange circles correspond to thermodynamically favorable states and large grey arrows correspond to kinetically favorable transitions. (d) **Kinetic time scales.** Distribution of MSM implied time scales for each sequence. The leading implied time scale corresponds to the characteristic time scale for hybridization/dehybridization and is approximately equal for all systems since simulations were conducted at the same concentration and at the respective melting temperatures. The higher order implied time scales correspond to a spectrum of kinetic relaxations between the constituent macrostates in the MSM corresponding to shifted and/or frayed states.

As illustrated in Fig. 3, we see that the NN model tends to predict lower free energies for each macrostate compared to the MSM and therefore overestimate macrostate stability relative to the hybridized (H) state by as much as 14.7 kJ/mol. (The free energy of the hybridized state is set to zero by construction for both the MSM and NN models.) The only exception to this trend is the frayed state (F4) unique to CG-core, where the MSM and NN predictions are in good agreement. Although the trends are in qualitative agreement, what is the root of the quantitative discrepancy of the MSM and NN models in the 5S2, 3S2, 5S4,

and 3S4 states? First, the MSM is constructed bottom-up from molecularly detailed 3SPN.2 simulations whereas the NN model is fitted top-down by regression against experimental data. There are approximations inherent in the 3SPN.2 model and the NN model was fitted to limited experimental data assuming a low-order expansion in terms of nearest neighbor additive contributions. Second, although 3SPN.2 is expected to capture some dangling end stabilization effects through base stacking and cross-stacking interactions, the model was not parameterized to fully capture the enthalpic contributions of the interaction of unbound bases with terminal base pairs, whereas this term is explicitly included within the NN model. [[Agree with this sentence?]] Third, a well known deficiency of the NN model is the absence of any treatment of inert tails – free bases that extend beyond the dangling end are known to destabilize the duplex.¹¹⁶

We can further explore the role of inert tails upon macrostate stability by analyzing the AT-all and GC-end sequences that occupy out-of-register shifted macrostates 5S2 and 3S2 comprising a one-base inert tail and 5S4 and 3S4 comprising a three-base inert tail (Fig. 2). For both sequences, our simulations show that 5S2 is both the most stable of shifted states and has the smallest discrepancy (4.0 kJ/mol AT-all, 10.0 kJ/mol GC-end) compared to NN predictions (Fig. 3b). The 3S2 and 5S4 states have nearly the same deviation from NN predictions (7.0-7.2 kJ/mol AT-all, 14.3-14.7 kJ/mol GC-end), indicating that longer tails in the 5' direction are as destabilizing as shorter tails in the 3' direction. It is known from differential scanning calorimetry studies¹¹⁷ that 3' inert tails are more destabilizing than 5' tails, with the differential behavior attributed to a combination of 5' tails preferentially stacking on the core duplex and 3' tails perturbing the duplex structure.¹¹⁶⁻¹¹⁸. Both the NN and MSM predictions for AT-all are consistent with this trend (i.e., $F_{3S2} > F_{5S2}$ and $F_{3S4} > F_{5S4}$). For GC-end, the MSM and NN models both predict the four shifted states to be less stable than the corresponding states in AT-all. This is in line with expectations since the terminal G:C pairs in GC-end decrease by two the number of available WC pairings in out-of-register shifted states compared to AT-all. The GC-end NN predictions run contrary

to the expectation that the 3' inert tails should be more destabilizing than the 5' tails, whereas the MSM predictions are consistent with this trend. Indeed, the MSM model for GC-end does not identify the 3S4 macrostate as a stable metastable conformation for the duplex.

In sum, the qualitative trends in the macrostate thermodynamic stabilities are in good agreement between the MSM and NN models, but show quantitative discrepancies for macrostates possessing inert tails. In these instances the NN model overestimates macrostate stability relative to the hybridized state by 4.0-14.7 kJ/mol. The MSM predictions are also consistent with the experimental expectation that 3' inert tails should be more destabilizing than the 5' tails, whereas the NN predictions can be in conflict with this trend.

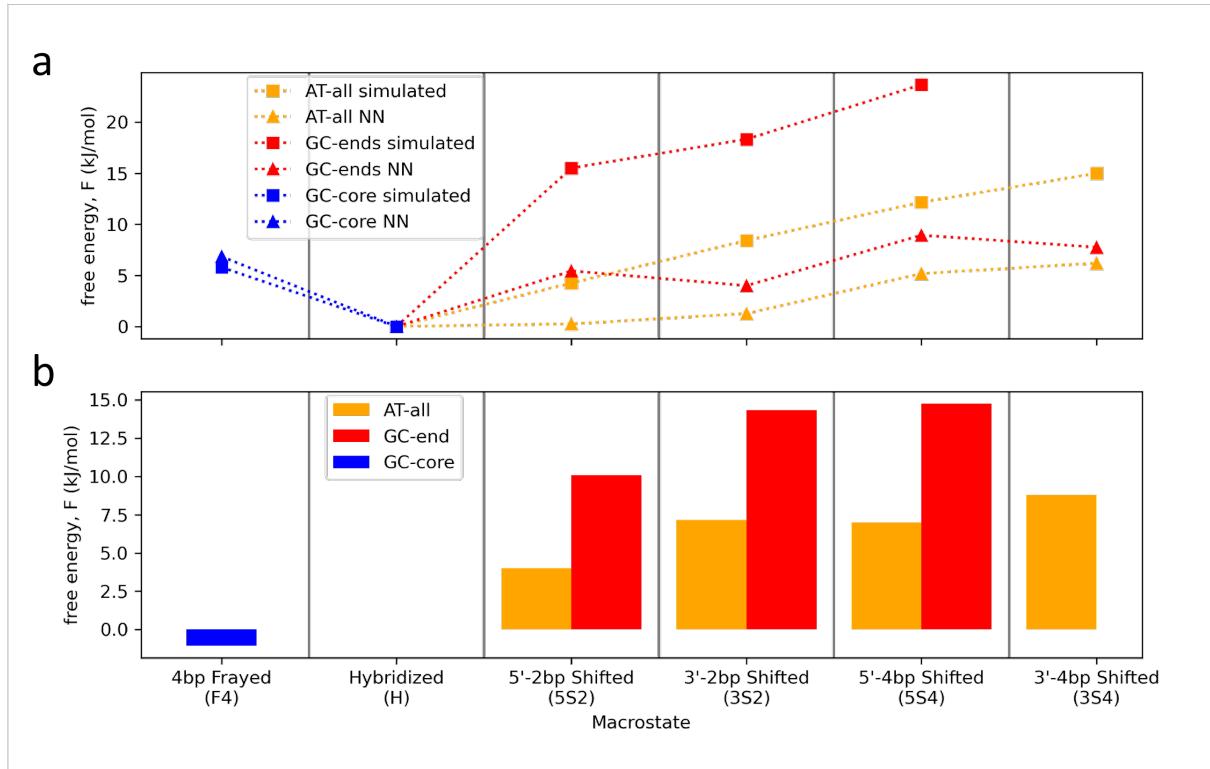


Figure 3: Comparison of the macrostate free energy predictions of the MSMs and nearest neighbor (NN) thermodynamic model.^{8,9} (a) Free energies of each macrostate relative to the hybridized state that is assigned a free energy of zero. (b) Discrepancy between the macrostate free energy predictions of the MSM relative to the NN model. With the exception of the F4 frayed state, the NN model predicts lower free energies than the MSM predictions.

3.4 Out-of-register states facilitate hybridization and dissociation dynamics (AT-all, GC-end)

In addition to thermodynamic stabilities, the macrostate MSM also furnishes quantitative and interpretable predictions of hybridization and dehybridization pathways and mechanisms. We now proceed to analyze these predictions for each of the four sequences and illuminate the relationship between sequence and dynamics. Two of our sequences, AT-all and GC-end, support out-of-register metastable states, and we commence our analysis with the role of these shifted states.

AT-all possesses the richest and most complex MSM of the four sequences by virtue of its repetitive nature, comprising a hybridized state (H), dissociated state (D), and four out-of-register shifted states (5S2, 3S2, 5S4, 3S4) (Fig. 2c). Analysis of the MSM transition probabilities reveal a critical role of the shifted states in mediating hybridization and dehybridization. Commencing from the dissociated state D, we observe approximately equal probabilities for transitions to each of the other five states, such that a transition to one of the out-of-register shifted states 5S2, 3S2, 5S4, or 3S4 is approximately 2.2 times more likely than a direct transition to the hybridized state H. Commencing from the hybridized state H, however, a direct transition to the dissociated state is approximately 1.2 times more likely than a transition to one of the two-base shifted states 5S2 or 3S2. Once in one of the four shifted states, the 5' vs. 3' overhang and degree of shifting play an important role in determining whether the duplex will transition to more shifted states, more aligned states, or completely dissociate. Transitions from more shifted states towards more aligned states (i.e., 5S4 → 5S2, 5S2 → H, 3S4 → 3S2, 3S2 → H) are approximately an order of magnitude more probable than the reverse transitions from more aligned states to more shifted states. The largest single transition probability from the four shifted states 5S2, 3S2, 5S4, and 3S4 is, however, back to the dissociated state D. Consistent with the higher destabilizing effect of 3' inert tails relative to 5' tails,^{116–118} the 3S4 → D transition probability is twice as large as the 5S4 → D, and the 3S2 → D is four times larger than the 5S2 → D. The transition proba-

bility from the 5S2 and 3S2 states back to the dissociated state D is equal to or greater than the transition probability to the hybridized state. A transition path theory analysis of the MSM reveals that 33% of productive hybridization trajectories $D \dashrightarrow H$ (where the dashed arrow indicates the combination of both direct and indirect pathways) proceed through one or more out-of-register shifted states. Among these out-of-register pathways, the $D \dashrightarrow 5S2 \dashrightarrow H$ transition is predicted to occur 57% of the time. A mean first passage time (MFPT) analysis returns a MFPT for $D \dashrightarrow H$ of $3.0 \mu s$ and for $H \dashrightarrow D$ of $2.5 \mu s$. These values are in close agreement with the leading implied time scale of $t_1 = XX \mu s$ reported in Fig. 2d and, as expected by the fact that the calculations are performed at the approximate melting temperature of the sequence, approximately equal to one another.

GC-end comprises the next most complex MSM with the introduction of the terminal G:C pairs maximally preserving the repetitive tract of A:T base pairings. The GC-end MSM possesses all of the same macrostates in its dynamical landscape with the exception of the 3S4 state (Fig. 2c). As discussed in Section 3.3, the 3S4 state is rendered unstable within the lag time of our MSM due to the presence of the destabilizing 3' inert tail and only four WC base pairings compared to six in the case of AT-all. Analysis of the transition probabilities reveal significant differences compared to those in the AT-all kinetic network. Commencing from the dissociated state D, we observe a similar transition probability to the 5S4 state as for AT-all, but once in the 5S4 state there are no significant transition probabilities to any other state except back to D. As such, the 5S4 state acts as a kinetic trap rather than as an intermediate to hybridization. The $D \rightarrow H$ and $H \rightarrow D$ transition probabilities are commensurate with those for AT-all. However, the $D \rightarrow 5S2$ and $D \rightarrow 3S2$ transition probabilities are half or less of those in AT-all, and the reverse transitions are an order of magnitude larger. This may be attributed to the reduced thermodynamic stability of the 5S2 and 3S2 states in GC-end that comprise only six WC pairs compared to eight in AT-all (Fig. 3). The $5S2 \rightarrow H$ and $3S2 \rightarrow H$ transition probabilities are more than an order of magnitude larger than in AT-all, which may again be attributed to the lower thermodynamic

stability of the two shifted states relative to the hybridized state H. Again, the transition probabilities out of the 3S2 state to D or H are comparatively higher than those out of the 5S2 state, consistent with the increased destabilizing effect of 3' inert tails.^{116–118} Commencing from the hybridized state H, a direct transition to the dissociated state is approximately seven times more likely than a transition to one of the two-base shifted states 5S2 or 3S2. A transition path theory analysis of the MSM reveals that only 7% of hybridization events D \rightarrow H and dehybridization events H \rightarrow D proceed through one or more out-of-register shifted states. The significantly reduced role for out-of-register shifted states in mediating the hybridization and dissociation pathways for GC-end relative to AT-all is consistent with the reduced thermodynamic stability of these states due to the elimination of possible out-of-register WC base pairing for the terminal G:C pairs and therefore a reduced accessibility of these states in the GC-end kinetic network. We compute a MFPT for D \rightarrow H of 1.6 μ s and for H \rightarrow D of 2.1 μ s, which are again approximately equal and in good agreement with the leading implied time scale of $t_1 = \text{XX } \mu\text{s}$ reported in Fig. 2d.

The out-of-register kinetic landscape that define AT-all and GC-end hybridization have been explored by a number of previous computational studies. Simulations have identified internal displacement mechanisms capable of correcting base pair alignment in 3SPN^{2,18} as well as in the coarse-grained oxDNA⁵³ and BioModi⁶² models. In all cases, these mechanisms were shown to be crucial components of the hybridization pathway for homogeneous and repetitive sequences. Xiao et al. performed an all-atom energy landscape-based analysis of 5'-GGGGGG-3' and 5'-GCGCGC-3' hexamers.¹⁷ Out-of-register states for 5'-GCGCGC-3' hexamers were identified as deep kinetic traps along the hybridization pathway and “slithering” through these states did not provide a significant hybridization pathway compared to an alternative “zippering” mechanism. (In contrast, slithering through out-of-register shifted states and zippering served as two parallel pathways for hybridization of 5'-GGGGGG-3'.) This stands in contrast to our results for our AT-all (5'-ATATATATAT-3') sequence, in which out-of-register states participated in 33% of productive hybridization events. It is conceiv-

able that the stronger hydrogen bonding in G:C WC pairs relative to A:T pairs may render out-of-register shifted states less favorable to hybridization by suppressing fluctuation-driven rearrangements,^{119,120} but additional studies would be required to reconcile these observations.

3.5 Central GC placement induces long-lived frayed states (GC-core)

The GC-core MSM represents a departure from the relatively rich and complex kinetic networks dominated by out-of-register shifted states to a much simpler one dominated by fraying (Fig. 2c). The MSM contains only three states – hybridized H, dehybridized D, and frayed F4. The F4 state is unique to GC-core and contains up to six WC pairs – the two central G:C core pairs and as many as four A:T pairs on one side or other of the core, while the other run of four A:T pairs remains free. (As expected by symmetry, the particular AT run that is made vs. free occurs with equal probability.) Our model reveals the absence of any direct hybridization or dehybridization transitions between the H and D states, with all pathways passing through the frayed state F4. Previous studies would suggest that hybridization of this sequence should proceed via a zippering mechanism, wherein upon formation of the strong central G:C WC base pairings the duplex helix should rapidly assemble in a middle-out fashion.^{16,53} Our results are partially consistent with this expectation, but reveal the frayed state F4 to be unexpectedly metastable, serving as a long-lived state with a mean life time of 1.8 ns. The stability of the state is attributable to the enthalpic stabilization offered by the up to six WC pairs and the entropic stabilization associated with the configurational entropy of the two free AT-tails.

Analysis of the transition probabilities show that commencing from the F4 state, progression to the hybridized state F4 → H is 25-times more likely than dissociation F4 → D. Thus once a D → F4 transition has occurred, a F4 → H transition will likely proceed; concomitantly, H → F4 events tend to fall back to the H state and are unlikely to proceed to

complete dissociation. The transition probabilities $H \rightarrow F4$ and $D \rightarrow F4$ are, respectively, one half and one quarter as likely as the $F4 \rightarrow H$ transition probability. We noted in Section 3.1 that fraying dynamics in the 3SPN.2 model appear to be significantly accelerated relative to center-of-mass translation, and it is conceivable that this may lead to elevated sampling of the $F4$ state within the computational model relative to experiment and the induction of more frequent dissociation. Moreover, since GC-core is the sequence most prone to fraying, this effect could be the root of the relatively poorer agreement of the k_d^{slow} response for GC-core compared to the other sequences due to an artificially elevated computational prediction of this rate (Fig. 1a). Nevertheless, under these caveats our model predicts a MFPT for $D \rightarrow F4 \rightarrow H$ of $3.4 \mu\text{s}$ and for $H \rightarrow F4 \rightarrow D$ of $2.9 \mu\text{s}$. Again these values are approximately equal and commensurate with the leading implied time scale of $t_1 = \text{XX} \mu\text{s}$ reported in Fig. 2d.

Lattice models have previously identified frayed states as putative intermediates in DNA hybridization/dehybridization.^{19,25,45} Araque et al. studied a 5'-ATGCGCAT-3' octomer using a lattice model and identified a symmetrically A:T frayed state as a crucial part of the duplex transition path.²⁵ We previously studied the four sequences that are the subject of the present work using T-jump IR and 2D IR spectroscopy and identified GC-core as possessing the highest deviation from two-state behavior during dissociation when neglecting out-of-register contributions.¹⁹ This result was interpreted to arise from loss of A:T contacts and fraying around the central G:C core, and this hypothesis was supported by lattice model calculations that predicted the GC-core conformational ensemble to possess substantially more frayed configurations than the other three sequences.⁴⁵ Follow-up T-jump measurements and Smoluchowski simulations on model 1D free energy landscapes showed that AT termini fraying was an effectively barrierless process characterized by rapid inter-conversion between all accessible frayed states.²⁸ These prior results are consistent with the present findings that expose the GC-core sequence to be the only sequence that occupies the $F4$ frayed state and therefore the only one possessing a metastable frayed state on time scales

exceeding the $\tau=1.2$ ns lag time of our MSMs.

3.6 Disruption of repetitive AT tracts promotes two-state “all-or-nothing” kinetics (GC-mix)

The GC-mix sequence is the only one of the four sequences studied that exhibits simple two-state “all-or-nothing” behavior.^{17,19,25,26} The GC-mix MSM comprises just two states, the hybridized H and dehybridized D (Fig. 2c), indicating that association and disassociation of the strands proceeds directly without passing through any metastable intermediate states resolvable under the $\tau=1.2$ ns lag time of our MSM. The two-state behavior appears to arise as a consequence of the placement of the G:C pair that maximally disrupts the repetitive AT tract within the decamer and destabilizing either out-of-register shifted states or frayed states. We note we do observe transient fraying of the terminal two-base AT tails within our dynamical simulations, but these frayed states are not sufficiently thermodynamically stable to produce a metastable macrostate within the resulting MSM. This stands in contrast to the metastable F4 state populated by GC-core, and can be understood by the reduced entropic stabilization offered by the frayed two-base AT tails relative to the frayed four-base AT-tails. Our MSM predicts a MFPT for $D \rightarrow H$ of $2.9 \mu s$ and for $H \rightarrow D$ of $2.3 \mu s$. Again, these are nearly equal and commensurate with the dominant leading implied time scale of $t_1 = \text{XX} \mu s$ reported in Fig. 2d.

Given the very simple two-state “all-or-nothing” behavior of GC-mix and the absence of any intermediate metastable states, we sought to interrogate our simulation trajectory data to elucidate the hybridization and dehybridization mechanisms. To do so, we followed all 10 intermolecular distances between native WC base pairs and tracked their evolution through a number of hybridization and dehybridization events. We present one representative example of each event in Fig. 4 and four more of each in Fig. S5. During the hybridization process, we observe a global decrease in all 10 distances as the strands approach one another, but uniformly observe the formation of some key native WC base pair contacts immediately prior

to duplex formation. Specifically, formation of one of the G:C WC pairs and at least one neighboring A:T pair or 2-3 central A:T pairs. This behavior is consistent with a “nucleation-zippering” mechanism as has been reported in previous studies.^{16,20,36,51} In dehybridization, we observe fraying on the two-base AT-tails on one or both sides of the duplex followed by rapid dissociation of the central WC base pairs. Qualitatively, we observed some short-lived states composed of two to four native WC base pair contacts immediately before full dissociation occurs, but, in contrast to the F4 state we observe in GC-core, these conformations do not constitute a metastable state within our MSM nor do they tend to reform intact duplexes. These dissociation dynamics are consistent with a “fraying-peeling” dehybridization mechanism.^{31,54,55}

3.7 Long-lived metastable states predicted by the MSM are resolved by T-jump IR

[[Rough cut largely for a suggested structure – please clean up and rework as you see fit based on your discussions with Brennan. I probably also screwed up some of the experimental jargon.]] We hypothesized that we should be able to validate particular kinetic predictions of our sequence-dependent MSMs using T-jump IR measurements. T-jump IR measurements commencing from low temperatures at which the hybridized state dominates the equilibrium ensemble apply a rapid step jump in temperature and probe the relaxation of the system to the dehybridized state. We hypothesized that sequences possessing long-lived intermediate states between the hybridized H and dehybridized D states may be detectable in a stretching of the time resolved T-jump IR t-HDVE signal. We report in Fig. 5a the predicted life times of each macrostate for each of the four DNA sequences at their respective melting temperatures. Only the AT-all sequence contains long-lived partially hybridized states with life times in excess of XX μ s and commensurate with those of the hybridized H and dehybridized D states. The longest lived of these is the XX state with a life time of XX μ s. GC-core also contains a number of out-of-register shifted states, but their life times are predicted to be XX-fold

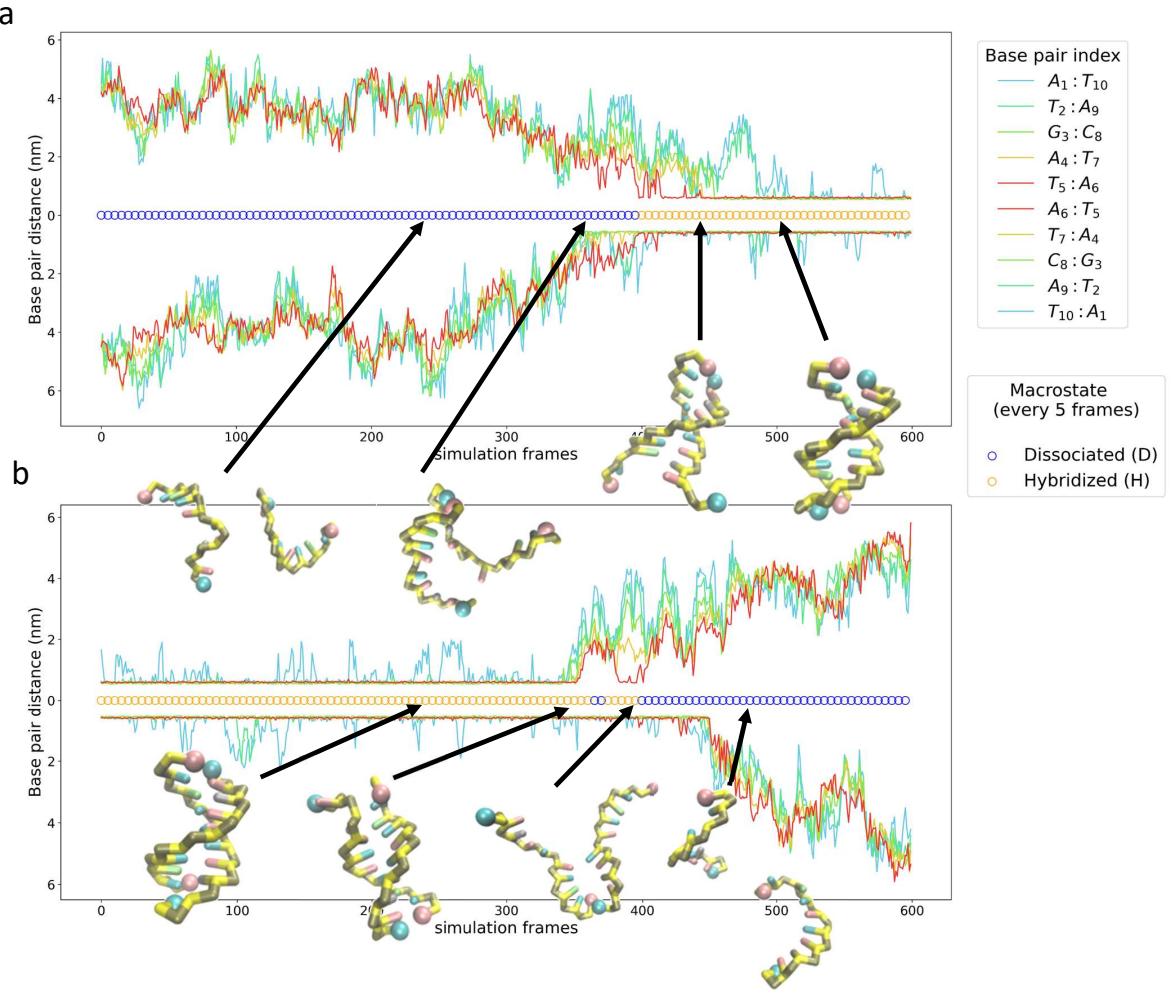


Figure 4: GC-mix hybridizes by nucleation-zippering and dehybridizes by fraying-peeling. Tracking of the 10 intermolecular distances between native WC base pairs over the course of an (a) hybridization event and (b) dehybridization event. Symmetrically permutable distances (e.g., $A_1 : T_{10}$ and $T_{10} : A_1$) are reflected across the x-axis to avoid congestion in the plot. Circles superposed on the x-axis indicate the instantaneous MSM state assignment as dissociated D (blue) or hybridized H (orange). Hybridization tends to occur by a nucleation-zippering mechanism, wherein a native G:C pair and adjacent A:T pair or 2-3 central A:T pairs first form prior to rapid formation of the complete duplex. Dehybridization tends to occur by a fraying-peeling mechanism wherein fraying of the two-base AT-tails on one or both sides of the duplex precedes dissociation of the central native base pairs and complete dissolution of the duplex. Four additional hybridization events and four additional dehybridization events are presented in Fig. S5.

shorter than that of the corresponding states in AT-all. This is likely attributable to their reduced stability due to the two fewer available WC pairings for any given out-of-register

GC-end state relative to AT-all. The longest lived GC-end intermediate state is only **XX** μs . The sole intermediate F4 frayed state occupied by GC-core has a life time of only **XX** ns, and the GC-mid sequence possesses no metastable states at all. Based on these predictions from our equilibrium MSMs, we hypothesized that the AT-all sequence possessing long-lived intermediate states with life times of up to **XX** μs should be distinguishable from the GC-end, GC-core, and GC-mid sequences predicted to have no metastable states or only very short-lived states with life times less than **XX** ns. We do not expect to be able to resolve the small differences between GC-end, GC-core, and GC-mid due to the very short-lived nature of these intermediate states.

We present in Fig. 5b-d [[Can we use some other color than yellow for AT-all in the time traces – it's quite hard to read.]] our T-jump IR t-HDVE difference spectra and corresponding normalized time traces at 1600 cm^{-1} and 1660 cm^{-1} . The signal at 1600 cm^{-1} corresponds to changes in A and T ring vibrations while the signal at 1660 cm^{-1} contains contributions from G and T carbonyl vibrations. Each time trace was fitted to the sum of a stretched exponential and two exponentials $S(t) = A \exp(-(t/\tau^{\text{fast}})^\beta) + B \exp(-t/\tau_{\text{slow}}) + C \exp(-t/\tau_{\text{cool}})$. The stretched exponential describes the relaxation process from 5 ns to 1 μs , and the two exponentials describe the signal increase from 1-320 μs and signal decay from re-hybridization induced by thermal relaxation back to the initial temperature. The fitting parameters A , B , and C correspond to the relative amplitudes of the three kinetic responses and the stretch factor β corresponds to [[What physical process.]] A testable prediction of our hypothesis is that the long-lived out-of-register shifted states in AT-all should result in a significantly smaller value for the fitted β parameter relative to those for GC-end, GC-core, and GC-mid. This hypothesis was supported by the experimental time series at both 1600 cm^{-1} , where $\beta_{\text{AT-all}} = \text{XX}$ compared to $\beta_{\text{GC-end}} = \text{XX}$, $\beta_{\text{GC-core}} = \text{XX}$, and $\beta_{\text{GC-mid}} = \text{XX}$, and 1660 cm^{-1} , where $\beta_{\text{AT-all}} = \text{XX}$ compared to $\beta_{\text{GC-end}} = \text{XX}$, $\beta_{\text{GC-core}} = \text{XX}$, and $\beta_{\text{GC-mid}} = \text{XX}$. This result provides an experimental validation of the kinetic predictions of the MSM models.

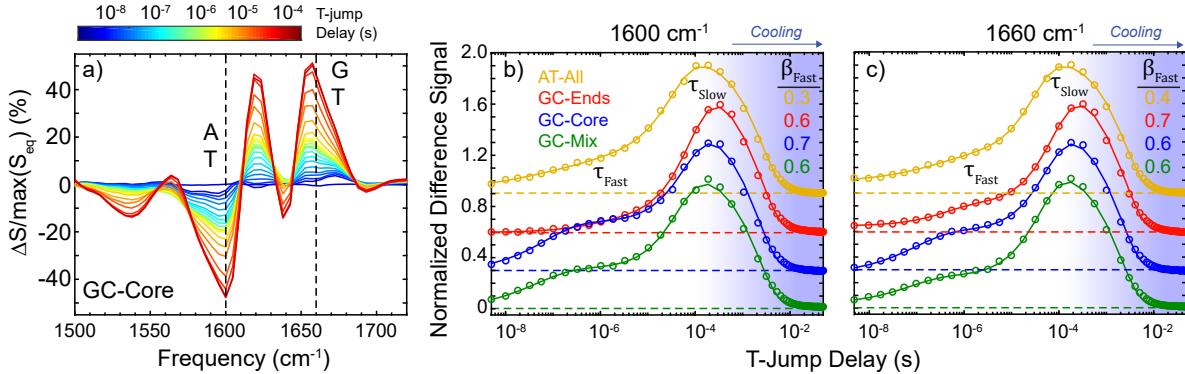


Figure 5: T-Jump IR responses reflect sequence-dependent conformational heterogeneity. (a) MSM predictions of equilibrium macrostate life times at the sequence melting temperature. (b) Mid-IR t-HDVE difference spectra for GC-core at time delays from 5 ns to 560 μ s. Normalized time traces for each sequence are shown at (c) 1600 cm^{-1} and (d) 1660 cm^{-1} . The signal at 1600 cm^{-1} corresponds to changes in A and T ring vibrations while the signal at 1660 cm^{-1} contains contributions from G and T carbonyl vibrations. Each time trace is fit to the sum of stretched exponential with two exponentials (solid lines): $S(t) = A \exp(-(t/\tau^{\text{fast}})^{\beta}) + B \exp(-t/\tau_{\text{slow}}) + C \exp(-t/\tau_{\text{cool}})$. The stretched exponential describes the process from 5 ns to 1 μ s, and the two exponentials describe the signal increase from 1-320 μ s and signal decay from re-hybridization induced by thermal relaxation back to the initial temperature. The stretch factor β for the fits at 1600 cm^{-1} and 1660 cm^{-1} are reported directly on the plots in panels c and d.

4 Conclusions

We have conducted an integrated computational and experimental study of the sequence-dependent kinetic mechanisms for the hybridization and dehybridization dynamics of a family of four self-complementary 10-mer DNA oligomers: ATATATATAT (AT-all), GATATATATC (GC-end), ATATGCATAT (GC-core), and ATGATATCAT (GC-mix). We conducted more than 1 ms of unbiased coarse-grained molecular dynamics simulations and employed deep learning techniques to construct high-resolution Markov state models as predictive and interpretable models of the sequence dependent dynamics. T-jump IR spectroscopy was used to calibrate the kinetic time scales of the coarse-grained molecular model and validate the kinetic prediction of the Markov state models that the AT-all sequence should possess long-lived out-of-register shifted states that are detectable within T-jump IR t-HDVE time traces.

Our results reveal that the specific placement of interrupting G:C pairs within an otherwise repetitive AT sequence can have a profound impact on the kinetic pathways and mechanisms for association and dissociation of the DNA duplex. In particular, we found AT-all to possess the richest and most complex kinetic landscape of the four sequences that is dominated by out-of-register shifted states that participate in 33% of hybridization and dehybridization events. Introduction of the G:C pairs at the end of the strand maintains an eight-base pair repetitive AT tract and the GC-end kinetic landscape possess all but one of the same out-of-register shifted states as AT-all. Destabilization of the GC-end shifted states relative to AT-all, however, results in a far more limited participation of these states with only 7% of GC-end hybridization and dehybridization events passing through one or more shifted states. Placing the G:C pairs in the center of the strand maintains two four-base AT tracts either side of the core and results in qualitatively different kinetic behaviors for GC-core. In this case, no metastable out-of-register shifted states are observed in our models with the hybridization and dehybridization pathways all passing through a strongly metastable frayed state in which one or other of the four-base AT-tracts is unbound resulting in two free AT-tails. Finally, placing the G:C bases between the center and end of the strand to maximally disrupt the repetitive AT tracts results in no metastable out-of-register or frayed states and results in simple two-state “all-or-nothing” hybridization/dehybridization behavior. Analysis of the specific pathways reveals hybridization to largely proceed by a nucleation-zippering mechanism and dehybridization to proceed by a fraying-peeling mechanism. The ordering of the computationally predicted kinetic landscapes from most to least complex – AT-all > GC-end > GC-core > GC-mix – with this trend largely dictates by sequence repetitiveness, specifically the number of consecutive AT motifs. We note that this ordering differs from our previously reported ordering in terms of deviation from two-state behavior of GC-core > GC-mix > AT-all > GC-end.^{19,28} We can understand these two apparently discrepant orderings by understanding that the latter was deduced based on experimental analyses and lattice models that did not account for out-of-register states and focussed largely on fraying

behaviors. Indeed, under the assumption that fraying is the dominant kinetic process relative to out-of-register shifting, we can harmonize the predictions of the present work with our prior work by eliminating all out-of-register shifted states in our fitted MSMs (Fig. 2c), in which case we find GC-core to contain an F4 frayed intermediate and the remaining sequences to all have simple two-state dynamics such that the predicted ordering is GC-core > GC-mix \approx AT-all \approx GC-end.

In sum, our results demonstrate the profound effect of sequence upon the kinetic landscapes, metastable states, and hybridization/dehybridization mechanisms of short DNA oligomers. Our analysis of this small family of sequences expose preliminary design principles for the (meta)stability of out-of-register and frayed states but we anticipate much greater richness in the landscapes will emerge with studies of longer and more diverse sequences. Going forward, we will extend this work to discern more general trends in sequence-dependent hybridization/dehybridization for a wider range of oligomer sequences and motivate strategies for experimental comparisons. We anticipate that these insights may provide foundational design rules by which to improve understanding of *in vivo* hybridization processes and rationally engineer optimized sequences for DNA nanotechnology applications such as DNA-PAINT⁷ and DNA barcoding.⁶

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