Lab-in-the-loop therapeutic antibody design with deep learning

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Abstract

Therapeutic antibody design is a complex multi-property optimization problem that traditionally relies on expensive search through sequence space. Here, we introduce "Lab-in-the-loop," a new approach to antibody design that orchestrates generative machine learning models, multi-task property predictors, active learning ranking and selection, and *in vitro* experimentation in a semi-autonomous, iterative optimization loop. By automating the design of antibody variants, property prediction, ranking and selection of designs to assay in the lab, and ingestion of *in vitro* data, we enable a holistic, end-to-end approach to antibody optimization. We apply lab-in-the-loop to four clinically relevant antigen targets: EGFR, IL-6, HER2, and OSM. Over 1,800 unique antibody variants are designed and tested, derived from lead molecule candidates obtained via animal immunization and state-of-the-art immune repertoire mining techniques. Four lead candidate and four design crystal structures are solved to reveal mechanistic insights into the effects of mutations. We perform four rounds of iterative optimization and report 3–100× better binding variants for every target and ten candidate lead molecules, with the best binders in a therapeutically relevant 100 pM range.

Keywords: Antibody design, deep learning, lab-in-the-loop, drug discovery

1 Main

Discovery of therapeutics is a fundamental driver of the extension of human life and health-span. Antibodies represent one of the most versatile classes of therapeutic modalities. The genetic modularity and biological mechanisms for rapid diversification underlying their production and maturation enable the jawed vertebrate immunological response to recognize almost any target molecule of interest, including proteins, peptides, and small molecules [1, 2]. As therapeutics, antibodies can be leveraged for immune system engagement or to deliver drug payloads with high specificity, creating strong demand for new antibodies to attack disease mechanisms at the source, leading to 58 new FDA-approved antibody therapeutics from 2019-2023 [3]. Unfortunately, antibody discovery and engineering remains a laborious and challenging process, adding to high development costs that influence the final cost of these medicines.

Antibody discovery campaigns commonly begin with immunization of animals with the target antigen, eliciting an *in vivo* immune response that can be quantified by analysis of the B-cell repertoire before and after immunization, typically by hybridoma or single B cell screening [4]. Alternatively, large libraries of 10^9-10^{11} naive antibody sequences can be expressed via display technologies (e.g., yeast or phage) and panned against the antigen directly *in vitro* [5]. Molecules must be optimized for antigen binding affinity, functional activity, immunogenicity, pharmacokinetics, expression, stability, solubility, viscosity, and aggregation propensity [6, 7]. The high-dimensional search space for antibody sequences has largely precluded first-principles approaches to antibody design, and the large cost, long timelines, and linearity of existing processes are prohibitive for the rapid development of new therapeutics [8] and cannot effectively manage the balance of multiple properties.

Machine learning (ML) and Bayesian Optimization (BayesOpt) are natural approaches for finding therapeutic antibodies in the high-dimensional search space of sparsely functional proteins [9–15]. Language models trained on protein sequence data have been used to guide directed evolution to affinity mature antibodies [16–19]. However, for drug discovery campaigns, ML methods must respect unique constraints for therapeutic molecules (e.g., developability, specificity, potency, expression, efficacy) and augment or outperform state-of-the-art molecular engineering approaches [6]. Prior work in ML for antibody design shows the immense promise of these approaches [16, 20]. However, in our hands these methods result in antibody variants that do not affect binding affinity and do not diversify the lead candidates, or introduce germline-reverting mutations that abrogate affinity. For therapeutic antibodies, we may require $\geq 3\times$ affinity maturation of an already matured antibody, with carefully chosen mutation locations to minimize immunogenicity risk. Unlike prior work, our optimization campaigns begin with reasonably optimized and viable clones from state-of-the-art *in vivo* discovery campaigns. Because of these stringent requirements and the complexity of the multi-property optimization problem outlined above, *de novo* protein discovery methods [21–23] do not obviate the need for optimization. Our approach takes steps towards respecting important therapeutic constraints[6], demonstrates generality across antigen targets and epitopes, and enables autonomous antibody engineering. Here, to address the limitations of both traditional discovery/engineering and prior ML-based design of antibodies, we introduce the "Lab-in-the-loop" (LitL) system.

We report results for four therapeutically relevant and biologically interesting antigen targets: Epidermal growth factor receptor (EGFR) [24], Interleukin-6 (IL-6) [25], Human epidermal growth factor receptor 2 (HER2) [26], and Oncostatin M (OSM) [27]. We discover at least $3\times$ better binding molecules to every single target, starting with lead antibodies from animal immunization hit discovery campaigns, and 10-100$\times$ better binders for multiple molecules. By leveraging an ensemble of generative models coordinated by a property prediction model for ranking and selection of designs, we achieve improvements across affinity, expression, and developability. We rationalize our results via experimental structure determination of 8 lead candidates and designs, as well as biophysics-based computational modeling of binding design complexes, showing that our designs preserve important interactions responsible for binding, while introducing up to eight new mutations that improve binding affinity. Our results demonstrate the powerful generalization capabilities of LitL to perform antibody design across diverse antigen targets and epitopes, without human intervention, while producing real therapeutic antibodies that are viable candidates to progress in the drug discovery pipeline.

2 Results

2.1 Lab-in-the-loop is a general machine learning system for autonomous drug discovery

LitL is a new approach for drug design that orchestrates loosely coupled ensembles of generative models, property prediction oracles, a ranking and selection algorithm, and experimental assays, all encompassed in an active learning loop to achieve iterative

optimization of antibody lead candidates (Fig 1**a**). Unlike prior work on biomolecular design with ML, which does not reflect the actual constraints and rigorous standards for success needed in drug discovery campaigns [6, 28, 29], LitL performs multi-property optimization, starting from lead candidate molecules, and operates across the human proteome of druggable antigen targets. In this paper, we focus on therapeutic antibody sequence space, although LitL is extensible to other therapeutic modalities. The selected example targets of EGFR, IL6, HER2, and OSM are of great interest in the treatment of cancer, inflammation, and autoimmune diseases [24–27].

Table 1: Lab-in-the-loop statistics.

Design round	Total designs	Expressors (> 0.01 mg)	Binders (> $4pK_D$)	Better binders (> 3×)
1	464	343	109	1
2	520	499	422	23
3	605	527	415	118
4	267	259	231	60

2.1.1 Generative models produce libraries of candidate molecules

Starting from a seed molecule that we aim to improve, the loop begins with the creation of a diverse library of sequences (i.e., the variants of the seed sequence) that is rich in high-quality candidate molecules. Generative models are trained on protein sequence data with the aim of emitting novel, diverse, functional proteins that are improved relative to sequences from *in vitro* or *in vivo* discovery and design campaigns. While *in vitro* and *in vivo* methods are restricted to sequences that are present in the display library or animal immune repertoire (which may require significant engineering before they are suitable for clinical trials), ML methods can generate near-limitless sequence diversity, optimize sequences with respect to multiple desirable properties, and enforce constraints on chemical liabilities and other molecular assessment criteria that would otherwise prevent molecules from advancing to clinical trials.

Generative models have various trade offs, generally between sample quality and sample diversity. To address the limitations of any particular generative model, we developed purpose-built methods for unguided sampling, sequence diversification, and hit expansion (e.g., Walk-Jump Sampling [30]) and separate generative methods for guided multi-property optimization (e.g., LaMBO-2 [31], DyAb [32], and Property Enhancer [33]). We include design proposals from multiple methods in each round, with the purpose of diversifying our design pool and maximizing our chances of success (as each method explores different parts of the antibody sequence space; see Supplementary Figures A4, A5, A6, A7).

We adaptively allocate experimental capacity to each method by combining the output of each method into a single combined library that is subsequently filtered and ranked by our active learning framework (i.e., global selection). In each round, all generative methods may produce up to 30,000 designs per lead molecule. This constraint is imposed to prevent any one method from dominating global selection

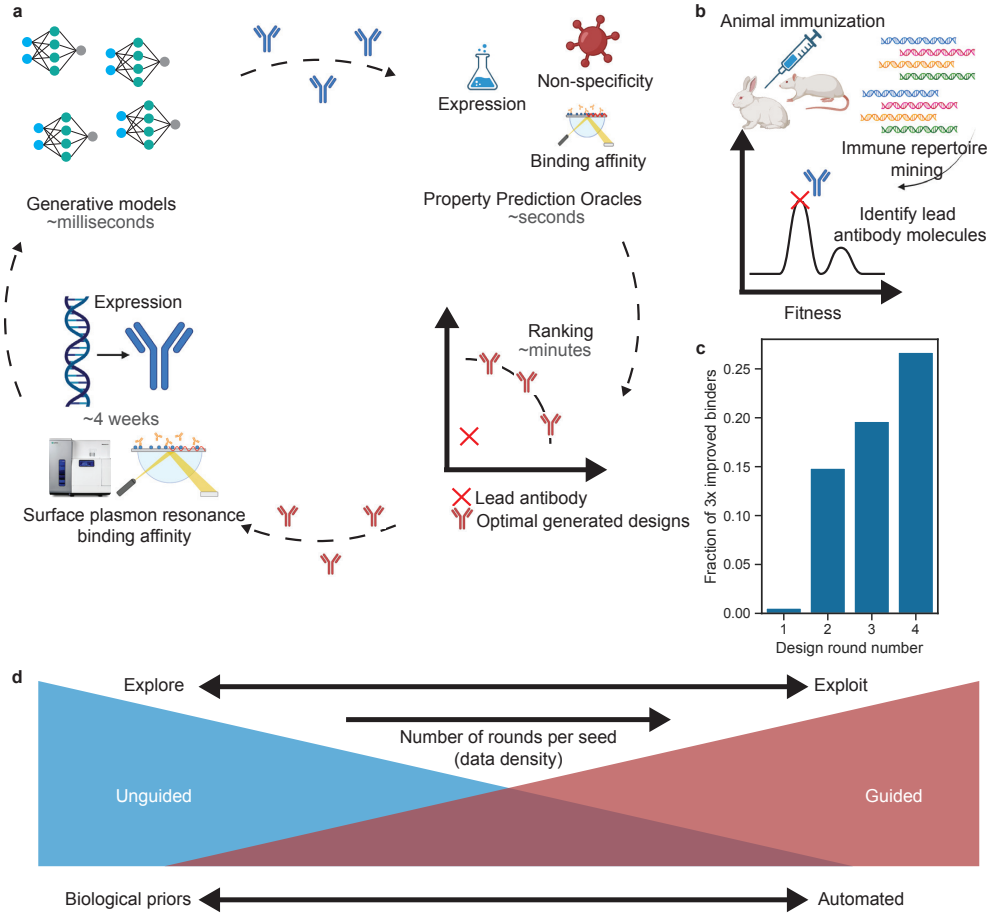

Fig. 1: **Lab-in-the-loop autonomous therapeutic antibody optimization. a**, Generative models produce a diverse *in silico* library of antibody sequence designs. Designs are ranked by property prediction oracles that are chosen, tournament style, based on their leaderboard performance evaluated on a hold-out split from the previous round of experiments. Predicted properties are used to rank designs to maximize the expected improvement compared to the lead antibody. Designs are expressed and binding affinity is measured to antigen targets with surface plasmon resonance (SPR). Lab data is used to re-train generative models and property prediction oracles for active learning. **b**, Lead antibody molecules are the best identified starting points from *in vivo* animal immunization and immune repertoire mining, although our approach can be initialized from any antibody discovery method. **c**, Lab-in-the-loop achieves monotonically increasing improvements in generating tighter binding variants over successive rounds of design. **d**, Ensembling unguided and guided generative models allows the LitL framework to dynamically explore and exploit regions of antibody sequence space.

by brute force, and to limit the computational cost of downstream *in silico* quality control. Details of these generative methods, their architectures, and training datasets, are presented in Section 4.1.1 of the Methods and their respective references.

2.1.2 Diverse molecule libraries are filtered and ranked for active learning selection

Given a high-quality library of designs, we then accurately estimate their therapeutic properties to determine which sequences to synthesize. In particular, generated designs are annotated with predicted properties encompassing expression, binding affinity, and non-specificity. All properties have associated binary labels (e.g., 1:1 binding to target antigen is or is not detected by SPR at a fixed concentration) modeled by binary classifiers, and expression yield and binding affinity are modeled as scalars by regression models. Out-of-distribution (OOD) detection methods introduced in [30] and additional quality control filters (e.g., chemical liability motifs) are also used to assist the discriminator by excluding very anomalous sequences or those with easily identified developability issues. Further details of these oracles, OOD detection methods, and quality control filters are presented in Sections 4.1.3, 4.1.4, and 4.1.5 of the Methods and their respective references.

The predicted properties for each design that passes quality control filters are then used to produce a global ranking of the designs that are predicted to perform best in laboratory experiments. The ranking model is the global arbiter of design selection. This systems-level design allows LitL to incorporate many diverse ideas and methods, while ensuring that all experimental successes contribute to improving the ranking model and oracles, which in turn improves the generative models, creating a flywheel of continuous improvement. The ranking algorithm picks designs that are *non-dominated*, that is, designs on the Pareto frontier of property space. We want to avoid expensive experimental assays for designs that are strictly dominated, i.e., designs for which we already have labeled antibody candidates with properties at least as good or better in all respects than the candidate design.

We select designs using the Noisy Expected Hypervolume Improvement (NEHVI) *acquisition function* [34] to mitigate the effect of property measurement noise, automatically induce diversity in sequence space that corresponds to diversity in property space, and balance the explore-exploit tradeoff induced by the conflicting objectives of improving the generalization capabilities of the discriminative models while still producing high-quality candidate molecules as soon as possible. Further details on the acquisition function and ranking are given in Section 4.1.6 of the Methods.

2.1.3 Experimental workflows drive the active learning loop

LitL is enabled by an efficient experimental pipeline capable of producing hundreds of high-resolution data points in parallelized, overlapping 4-6 week timelines. To enable the accelerated timelines of LitL, we developed an optimized antibody production pipeline utilizing Gibson-assembled linear fragments (GLFs), as previously described [35]. Briefly, variable region sequences are synthesized as linear DNA fragments (Twist Bioscience) and subsequently integrated into GLFs containing all elements required

for transient expression at the 1mL scale utilizing HEK293 cells. The linear DNA based expression workflow trims multiple cloning steps, saving significant time and cost while also being highly amenable to automation. After expression, antibodies are affinity purified and concentration is measured by optical density. Binding affinity of the designed and lead antibodies is measured by surface plasmon resonance (SPR). Further details on experimental methods are presented in Section 4.4 of the Methods.

2.1.4 Lead antibody candidates are obtained from *in vivo* discovery campaigns

The lead antibody candidates are obtained from state-of-the-art *in vivo* immunization of genetically engineered animals and immune repertoire mining techniques (Fig. 1**b**) [4]. Repertoire mining produces natural, developable lead molecules and additionally provides unlabeled local neighborhoods (in sequence space) of likely binders around lead antibodies, which is invaluable for initial training sets of generative and property prediction models. However, the LitL approach is fully general and starting seeds can also be obtained from rationally designed yeast surface display [36] libraries and *in vitro* discovery campaigns. Further details on seed selection are presented in Section 4.4.2 of the Methods.

2.2 Lead candidates are affinity matured via iterative optimization

Before presenting the detailed sequence-level results of LitL, we highlight the top level experimental success of the LitL approach. For simplicity, our top line metric of success for a design is a strict threshold of at least 3× improvement in measured binding affinity compared to the lead antibody. This unambiguously establishes a criterion for "better binding", beyond any uncertainty induced by measurement noise. In Fig. 1**c**, we show the fraction of total designs that are 3× better binders discovered in each round. In the first round of LitL *no labeled data is available* in the neighborhoods of the starting seeds. By the fourth round, LitL produces a design library of >26% 3× better binders. Figure A1 shows the cumulative number of labeled designs for each seed over design rounds.

While affinity maturation is not our only optimization goal, it is a major focus of therapeutic antibody design to take strong binding, developable lead antibodies and engineer at least nanomolar binding before promoting leads to later stage development. For convenience, we represent binding affinity as a negative log transform of the equilibrium dissociation constant,

$$pK_D = -\log_{10}(K_D) = -\log_{10}(k_d/k_a) \tag{1}$$

where k_d is the dissociation rate (off rate) and k_a is the association rate (on rate). Fig. 2a shows a histogram of all LitL designs and their difference in binding affinity (ΔpK_D) compared to their respective lead antibodies. The dashed vertical line indicates a 3× improvement in binding affinity, such that all designs to the right of the line are at least 3× better binders ($\Delta pK_D = 0.47712$) than their respective lead molecules. A similar

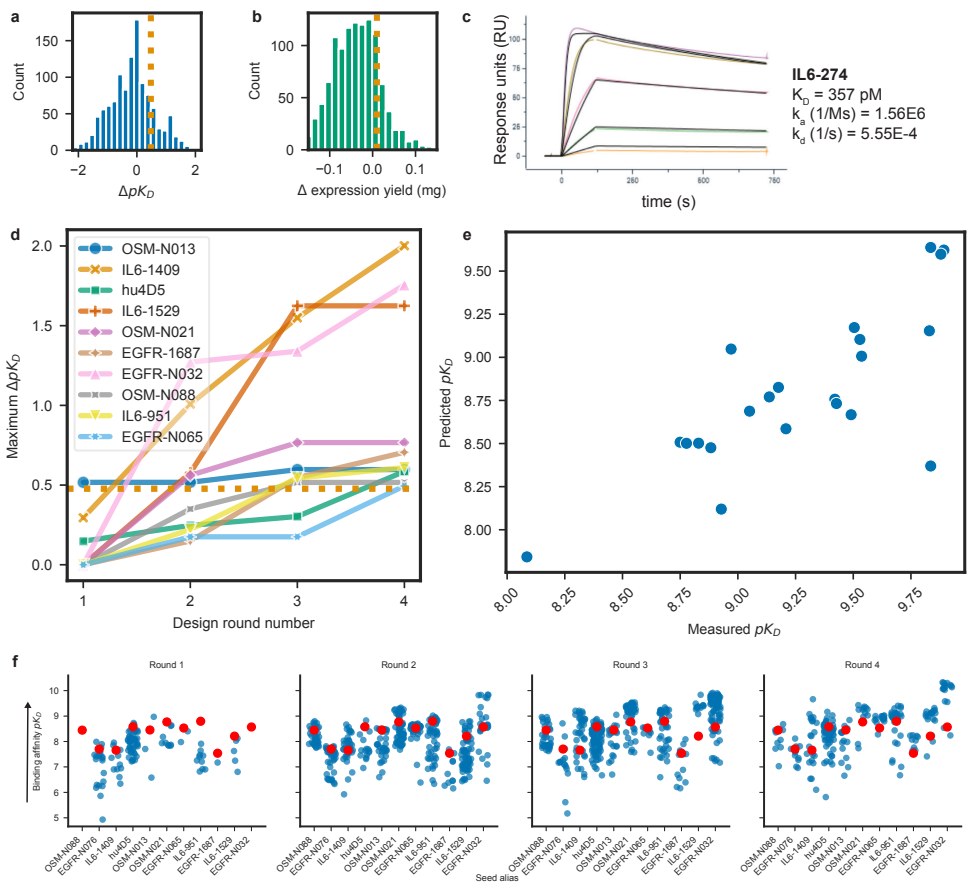

Fig. 2: Therapeutic antibody lead optimization via affinity maturation with lab-in-the-loop. **a**, Histogram of change in binding affinity (ΔpK_D) for all designed antibodies. The dashed vertical line denotes a 3× improvement in binding affinity. **b**, Histogram of change in expression yield (mg) for all designed antibodies. The dashed vertical line denotes a 0.01 mg improvement. **c** Representative SPR sensogram for a 357 pM binder to IL6. **d**, Max improvement in binding affinity for 10 different lead antibodies across four different antigen targets. The dashed horizontal line indicates a 3× improvement in binding affinity. **e**, Predicted versus measured pK_D for 22 of the highest binding affinity designs. **f** Absolute measured pK_D (higher is better) of designs (blue) and lead molecules (red) over design rounds.

histogram for expression yield is shown in 2b, where the dotted line corresponds to 0.01 mg, the amount of antibody required to run SPR. An example SPR sensogram binding curve (Figure 2c) illustrates how the affinity values are derived from curve fits. Across four antigen targets and ten distinct lead molecules[1], the improvement in pK_D for the

[1] We considered 12 total starting seed molecules. One of these seeds failed to express. Designs from one seed underperformed the rest in the first round of iterative design. Our active learning framework (acquisition

best LitL design over rounds is shown in Fig. 2d. The horizontal dashed line indicates a 3× improvement in binding. For ten lead molecules, LitL successfully discovers better binders that meet our pre-specified threshold for significant affinity maturation. For four of the lead molecules, LitL discovers better binders with $\Delta pK_D > 1$, which denotes a 10× increase in binding affinity. In Figure 2e we show predicted versus measured pK_D for 22 of the tightest binding designs derived from each seed, across over a log-fold difference in binding affinities. Figure 2f shows the absolute measured pK_D for designs (in blue) over rounds and their respective seeds (in red).

2.3 Multi-property optimization enables therapeutic antibody design

In addition to initializing our optimization efforts from developable, natural antibodies derived from *in vivo* immune repertoire mining, we further constrain our designs to account for non-specificity, expression yield (which impacts downstream characterization assays that require specific amounts of protein material), and *in silico* developability risks. In Fig 3**a** we show the lead candidate molecules in dark blue and the best binding variant designs for each seed in light blue, after computing *in silico* metrics with the *Therapeutic Antibody Profiler* (TAP) [37]. These metrics, derived from the variable domain antibody sequence, flag sequences that are out-of-distribution with respect to the *Therapeutic Structural Antibody Database* (Thera-SAbDab). All but one of our best binding designs are within the TAP guideline ranges; one design is just over the threshold for positive and negative charge in the CDRs. LitL avoids drastic biochemical and biophysical changes that would induce avoidable developability risks, while achieving many-fold improvements to binding affinity.

To estimate risk of non-specific binding interactions of our designs, we developed a surrogate model trained on internal BV ELISA data. BV ELISA [38] is an assay developed to assess non-specific binding (further details are provided in Section 4.4). A BV ELISA score > 1.0 indicates a non-specificity risk; we confirm that all of our designs fall below the predicted risk threshold (Fig 3**c**). For 67 designs, we also engineer out chemical liabilities while maintaining or improving binding affinity (Fig A8). Chemical liabilities include deamidation ('NG') and glycosylation ('N*[ST]') motifs, and other easily recognizable substrings that pose developability risks. The per-round Pareto frontier of designs with respect to expression concentration and binding affinity (Fig 3**d**) illustrates how successive design rounds expand the Pareto frontier, finding non-dominated designs.

2.4 Modeled interface structures of designed antibodies demonstrate epistatic interactions

As all designs reported in this work were produced with sequence-only models, we considered whether their effects on affinity could be rationalized structurally (Fig 4). We

function) automatically prioritizes molecules with the largest expected improvement to binding affinity for each target, regardless of starting seed, so this seed was not prioritized in subsequent rounds of design and no affinity matured designs were generated.

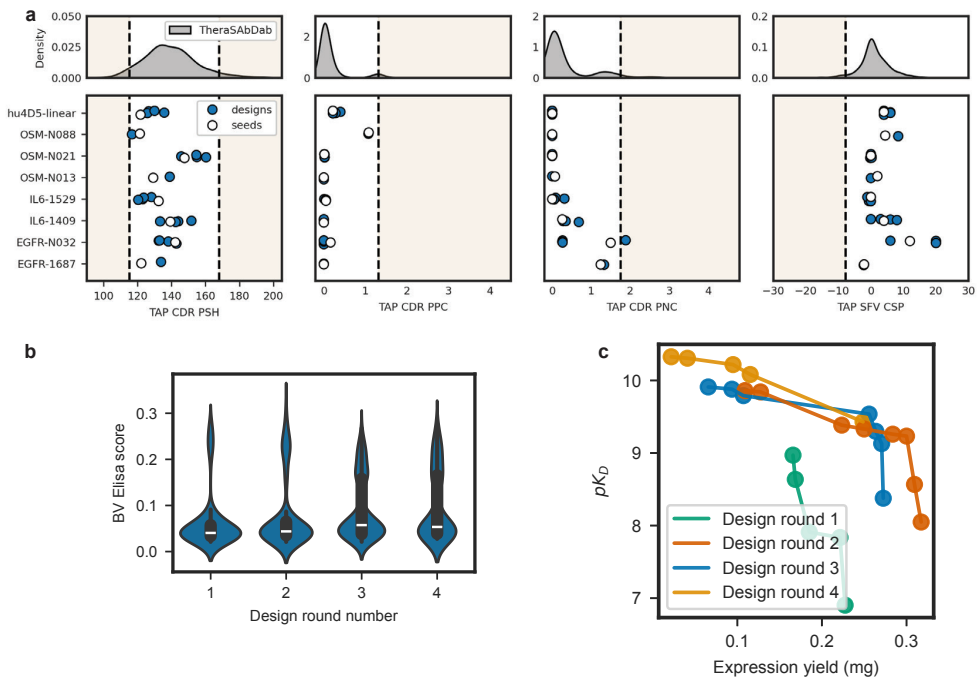

Fig. 3: Multi-property optimization of lead candidates includes improving expression yield and *in silico* developability properties. **a**, All but one of the tightest binding design variants stay in acceptable ranges for developability guidelines given by the Therapeutic Antibody Profiler. **b** Predicted BV Elisa scores, from a surrogate model trained on BV Elisa data, a measure of non-specificity. BVE scores < 1.0 indicate no non-specificity risk. **c**, Pareto frontier of non-dominated designs on the pK_D versus expression yield property landscape for each design round.

first investigated two designs that achieved >4× improved binding ($\Delta pK_D = 0.688$ (ERBB2-P00873, 5 edits, 1 insertion) and 0.638 (ERBB2-P00965, 8 edits, 1 deletion)) relative to the anti-HER2 antibody Trastuzumab ($pK_D = 8.3$). From 10 independent minimizations of the native crystal structure (PDB ID: 1N8Z), we determined a union set of 17 antigen-contacting residues in the CDR loops through energetic analysis with Rosetta [39, 40] (Fig 4**a**). Modeling the singular edit at an existing heavy-chain contact (HC:N65Q in CDRH2)—a region with highly dynamic interactions (alternative rotamers in 4/10 simulations for HC:Y67, 3/10 for Ag:E558)—revealed a new hydrogen bond to HC:Y67 that stabilizes a multi-residue chain of interfacial contacts (4**a** inset), demonstrating that direct optimization of interface positions indeed occurs and may exhibit epistatic effects on binding. However, all other edits made across both designs (Supplementary Figure A10) are distinct from the native contacts, with many outside the CDRs, including an insertion in one design and a deletion in the other. Furthermore, the two designs employ orthogonal edits, only sharing one position with different mutations (HC:S73R and HC:S73A) that is distant from the antigen and thus

plausibly a neutral mutation. Folding of both sequences confirmed that the structural integrity of non-CDRH3 loops was maintained despite these changes (Supplementary Figure A10).

This interface structure analysis suggests that our sequence-based design methods learn important structural and biophysical priors, resulting in optimized designs that preserve or optimize important energetic contacts necessary for binding, while introducing potentially epistatic mutations that improve binding affinity. Affinity maturation can occur via multiple routes [41] using distinct mutations that are not necessarily physically localized near the interface nor the antigen. We find that insertions and deletions are successfully introduced by our models and are tolerated, but not generally necessary for optimization.

2.5 Crystal structures of designed antibodies reveal mechanistic roles of mutations

To experimentally verify the varied effects of designed mutations across a broader range of targets, we obtained apo crystal structures of four seeds and four designs (Supplementary Table A2, Supplementary Figure A11), in addition to two previously published (9MU1 and 9MSW [32]), spanning three unique targets (Fig 4**b**). SPR kinetic parameters and affinities are reported for all designs in this figure in Supplementary Table A3. For the non-OSM seeds, all crystallized designs are >10× improved binders. We observed remarkable conservation of overall CDR loop structure in 5/6 designs (consistent with predicted structures in Supplementary Figure A2), primarily through newly introduced hydrogen-bonding interactions (Fig 4**b** insets) that serve to further reinforce the seed loop conformation, which may contribute to affinity improvements via structural stabilization. Several other mutations make no new interactions with other residues (e.g. the mutations on CDRH2 of 9MUZ) but are highly solvent exposed and thus may constitute direct contacts to the antigen that are introduced without adversely affecting the native backbone.

The exception to this arose in the structural series for seed OSM-N021, where isosteric packing of GY mutations in the stem region of CDRH3 for design 9N7M ($\Delta pK_D = 0.56$, 3.6× improvement) retained the conformations of all CDR loops, yet SY mutations at the same positions in design 9N7O ($\Delta pK_D = 0.65$, nearly 4.5× improvement) produced an alternative loop conformation via novel hydrogen-bonding interactions that may contribute to its affinity maturation by more directly exposing the CDRH3 residues. All three OSM seeds proved recalcitrant to optimization (along with hu4D5-linear, IL6-951, EGFR-N065; Fig 2**d**,**f**), though we note that these all have starting pK_D values of >=8.3 (5 nM) and thus may be close to their local optima. It is therefore plausible that, in contrast to the native-contact-preserving edits to hu4D5-linear (Fig 4**a**) and the conformation-stabilizing edits to the other seeds (Fig 4**b**), the structural changes induced by edits in 9N7O may actually be critical to pushing affinity out of a local optimum imposed by the native backbone. The rarity of this occurrence is suggestive that structural consistency imposed by training data and filters (see "Biophysical Priors" in Section 4.1.2 of the Methods) is only sacrificed where more conservative mutations are insufficient.

3 Discussion

Here, we introduced the "Lab-in-the-loop" (LitL) system for continuous optimization of lead antibody candidates for multiple properties, most notably binding affinity and expression, against 4 distinct antigens of therapeutic interest: EGFR, OSM, HER2, and IL-6. LitL orchestrates generative and discriminative machine learning methods to explore sequence space, while remaining tightly coupled to high-quality, medium-throughput affinity and expression experimental feedback via active learning. Over four experimental iterations, we produced >3–100× higher binding affinity antibodies for ten lead molecules to four different antigen targets, while simultaneously retaining or improving upon multiple other essential properties. Apo-state crystal structures of ten lead candidate and affinity matured designs (two previously published [32]) unambiguously demonstrated that LitL generates and selects designs possessing therapeutically relevant affinities (>10× improvement) while retaining the seed CDR loop conformations, in part through newly introduced rigidifying mutations and stabilizing intramolecular interactions. The models and filters described herein span both sequence and structural inputs, incorporating domain knowledge, biophysical priors, bioinformatics data, and model-driven *in vitro* data generation. We further demonstrate that sequence-based generative models can produce structurally interpretable mutations when a seed co-complex is available.

Because of the complexity of drug discovery, an immensely challenging multi-property optimization problem driven by low-throughput, noisy experimental feedback, we find that employing machine learning systems and ensembling over computational methods is necessary to mitigate the limitations of any particular approach and address all the relevant challenges. Future work will unite these capabilities and parts of the drug discovery process beyond early stage discovery into an "end-to-end" machine learning system. By demonstrating acceleration of state-of-the-art experimental antibody engineering for therapeutic candidate antibodies and tackling the complexity of therapeutic discovery campaigns, we believe that LitL represents a significant step towards realizing the promise of ML and computation in large molecule drug discovery.

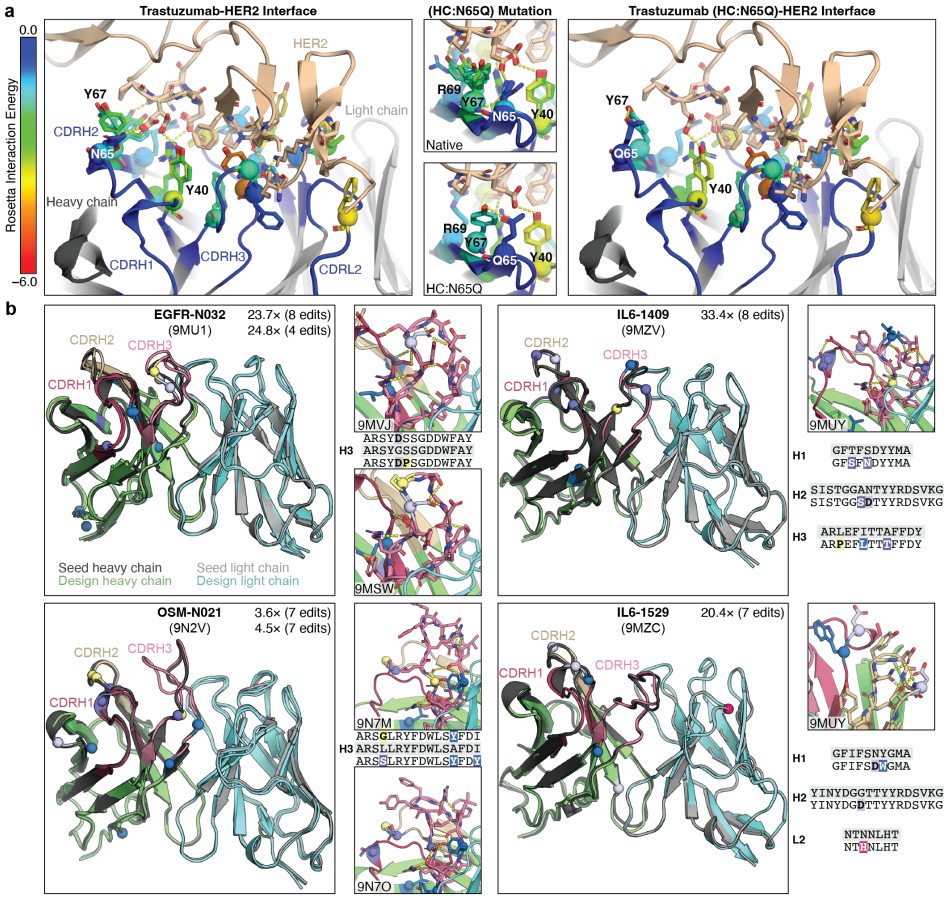

Fig. 4: Interface structure modeling and experimental structure determination yield mechanistic insight into mutational effects. **a**, Native interactions from multiple replicate minimizations of Trastuzumab (hu4D5-linear) are shown as spheres and colored by Rosetta interaction energy (more negative is stronger), with hydrogen bonds depicted as yellow dashes. The CDRH2 interactions are highly dynamic, exhibiting multiple rotameric conformations with variable binding energy. Upon modeling the only mutation at a native contact from two separate >3× binders (HC:N65Q), a new hydrogen-bond between Q65-Y67 stabilizes the rotamers (highlighted in insets). All other mutations are separate from the native contacts (see Supplementary Figure A10), and also appear several places in the framework region, indicating that they act by indirect effects. **b**, Crystal structures of four seeds and six designs highlight very high structural consistency in almost all cases. For each design, the fold-increase in affinity and number of edits is specified. Edit positions are colored as: nonpolar (blue), polar (purple), negatively charged (lavender), positively charged (magenta), and conformational (yellow). The insets highlight regions of notable new interactions, primarily in CDRH3. Except for 9N7M, at least one edit in each design expands the intramolecular hydrogen-bond network within the CDRs. For the selected CDR sequences reported, the seed sequence is on a grey background and design sequences (insets) have mutations highlighted to match the renders.

4 Methods

4.1 Computational methods

4.1.1 Generative models

Unguided sampling for hit diversification. Unguided sampling for hit diversification is performed with discrete Walk-Jump Sampling (dWJS) and the Sequence-based Variational Diffusion Model (SeqVDM), introduced in Frey *et al.* [30]. dWJS is a generative model that combines separately trained score- and energy-based models (EBM) to learn a smoothed distribution of *noisy* data, sample noisy data from this smoother space with Langevin Markov Chain Monte Carlo (MCMC) and gradients from the EBM, and then denoise to "clean" data with the score-based model. dWJS builds on the Neural Empirical Bayes [42] formalism and generates 97-100% expressing and up to 70% functional, binding antibodies in *in vitro* experiments [30]. SeqVDM is adapted from [43] for protein sequences; it projects discrete sequences into a continuous latent space and performs denoising diffusion in the latent space. Further details for both dWJS and SeqVDM are provided in [30].

Guided sampling for lead optimization. Latent Multi-Objective Bayesian Optimization (LaMBO-2), introduced in Gruver & Stanton *et al.* [31], and Property Enhancer (PropEn) [33], are used for lead optimization via guided sampling. LaMBO-2 is a method for controlled categorical diffusion that enables sampling high likelihood, expressing protein sequences that are optimized with respect to an acquisition function, enabling multi-objective design. PropEn is a model designed to implicitly guide design optimization without the need for training a separate discriminator. Instead, PropEn leverages a matched training dataset. Initially, each sequence in the dataset is paired with a similar sequence that exhibits superior binding properties. A Seq2Seq model is then trained to take a lower affinity sequence as input and reconstruct its higher affinity counterpart. DyAb [32] leverages pairwise representations to predict property differences between antibody sequences. Here, it was employed as a ranking model to score combinations of known mutations, and as a generative model when combined with a genetic algorithm. More details regarding DyAb can be found in [32].

4.1.2 Biophysical priors

Domain knowledge related to antibody engineering and protein design are incorporated into generative methods in the form of biological priors to restrict the high-dimensional search space and improve the rate of producing designs that bind to the antigen of interest. All the generative models used in this paper are *sequence-based* models; they are trained on amino acid sequences and emit amino acid sequences. While no protein structures are explicitly generated by our methods, protein structure information is included via strong biological priors. Models are trained on AHo-aligned [44] antibody sequences, a scheme with particular emphasis on structural consistency. AHo alignment introduces alignment tokens ("-") and ensures a global sequence alignment across all antibodies, clearly separating an antibody sequence into distinct structural elements (framework and complementarity determining regions (CDRs)).

Training on aligned sequences [30, 31, 45, 46] is an established method for improving the performance of protein generative models and implicitly providing a strong structural prior. AHo alignment also enables our methods to easily introduce length changes (insertions or deletions), by sampling alignment tokens. However, at sampling time we often mask out the alignment token, preventing length changes, which may attenuate binding. Similarly, some designs restrict mutations to only the CDRs or subsets of the CDRs, which are generally thought to be most important for binding, though it is known that framework positions can also dramatically impact affinity, both individually [47, 48] and as part of humanization[49]. Our biophysical priors and design methods are built to preserve the binding mode of the seed antibody [50].

4.1.3 Property prediction models

Multi-task fine-tuning. For each LitL round, denoted by t, we first perform *discriminative model selection*, using the generalization error on the last round $(t-1)$ to estimate the generalization error on the next round. A uniform random holdout set can be used as the validation set at $t = 0$. The best performing oracle is used for each property, as measured by a pre-determined metric on the hold-out set. Framing model selection as an open competition encourages rapid development of surrogate models and ensures that a diverse range of ML approaches are tried for challenging biological properties. An exceptionally performant model emerged during LitL competition: Cortex [31], a multi-task fine-tuning framework that uses pre-trained Language models for Biological Sequence Transformation and Evolutionary Representation (LBSTER) [51] to simultaneously model all properties of interest.

Pre-trained representation learning. Language models for Biological Sequence Transformation and Evolutionary Representation (LBSTER) is used for pre-training representation learning models for multi-task property prediction and optimization with Cortex. LBSTER includes both Masked Language Models (MLMs) based on the ESM-2 model architecture [52] and Causal Language Models (CLMs) based on the Llama-2 model architecture [53]. LBSTER models are trained on Uniref50 [54] and the Observed Antibody Space [55], de-duplicated with MMSeqs2 [56]. We use the protein language model cramming strategy introduced in Frey *et al.* [51] to pre-train performative LBSTER models in only a few GPU days.

4.1.4 Out-of-distribution detection

OOD detection is performed on designed sequences to determine if they are in-distribution for property prediction models and therefore can be reliably ranked by the ranking model. OOD detection is implemented with the distributional conformity score (DCS), as introduced in Frey *et al.* [30], which is a measure of how likely generated samples are with respect to a reference set of already known binders or expressors. DCS uses a likelihood under a joint density of statistical properties, including log-probability under a protein language model, and sequence-based properties like hydrophobicity and molecular weight, calculated with BioPython [57]. Kernel density estimation (KDE) is used to compute the joint density, although any density estimator may be used.

4.1.5 Filters and quality control

Designs are annotated to ensure that they do not introduce chemical liabilities (e.g., glycosylation and deamidation motifs) and that conserved amino acids in antibody sequences are preserved (e.g., canonical cysteines). Additional quality control checks are performed to prevent germline reversion (which may lead to affinity attenuation). Further constraints are imposed across all designs and specific generative models to encourage generative models to explore local neighborhoods in sequence space around lead antibodies, so that designs are more likely to be in-distribution for property prediction models. In the first round of design, a maximum edit distance cap of 6 edits from the lead is enforced. In the second round, this cap is increased to 8, and in the third round, it is increased to 12. Some generative models restrict edits to particular regions (e.g., dWJS only introduces mutations in CDRs), while other methods including PropEn and LaMBO-2 introduce mutations across the entire sequence.

4.1.6 Ranking and active learning

We use Noisy Expected Hypervolume Improvement (NEHVI) [34] as our acquisition function to optimize the selection of designs with respect to multiple properties $\mathbf{x} \in \mathcal{X}$ that we represent as a vector-valued function $f : \mathcal{X} \to \mathbb{R}^m$. Because this is a multi-objective optimization problem, we are looking for *non-dominated* (i.e., Pareto optimal) designs. A design, x_1, dominates another design, x_2, if it no worse than x_2 for all properties and strictly better for at least one property. We seek to produce and select a set of non-dominated designs to assay in the lab in each successive iteration of LitL. In general, the properties we care about are *black-box* objectives, with no closed-form expression, so we learn about these distributions via expensive, slow, noisy measurements.

To select a "batch" of designs, we obtain a posterior distribution $p(f|D)$ over functions for real properties, given a dataset, D, of measurements. We choose a reference design x_{ref} as a lower bound and never choose any design that is predicted to be worse than x_{ref} for any property. When considering whether a design should be added to our batch, we compute its "hypervolume improvement" (HVI), which is the difference in hypervolumes (in property space) between the design and the designs already in our batch. Finding the subset of $\mathcal{X}$ that maximizes HVI is an NP-hard problem, but a greedy algorithm works quite well. To account for epistemic uncertainty, we rely on surrogate models and marginalize f, yielding the noisy expected HVI (NEHVI) for a design x',

$$\text{NEHVI}(\mathbf{x}') = \mathbb{E}_{f|D}[\text{HVI}(\mathbf{x}')]. \tag{2}$$

4.1.7 Interpretability

Sequence-level interpretability is performed with Cortex, as described in Adebayo *et al.* [58]. Independent Gaussian noise corruption is introduced as a computationally efficient alternative to adversarial training, without deteriorating classifier performance. Gaussian corruption is shown to confer faithfulness to feature attributions, i.e., saliency maps computed with classifiers that are regularized during training with

Gaussian corruption correctly ignores spurious distractor features. This regularization allows inspection of gradient-based saliency maps to determine the residues and mutations that classifier predictions are most sensitive to.

4.1.8 Rosetta biomolecular modeling

Input structures were prepared using Rosetta [39] gradient descent minimization followed by FastRelax [59, 60] with the *beta_nov*16 scorefunction [40] and the following flags:

```
-corrections:beta_nov16 -ex1 -ex2 -use_input_sc -flip_HNQ -no_optH
false -packing:repack_only true -relax:constrain_relax_to_start_coords
-relax:ramp_constraints false
```

In the case of the seed hu4D5-linear (Trastuzumab), coordinates were obtained from PDB code 1n8z. The HC:N65Q mutation was introduced using the MutateResidue mover. The entire structure was first minimized using MinMover then the interface was allowed to repack using FastRelax (InterfaceRelax2019 script) with nonramping backbone constraints to the starting coordinates applied during both steps. This MinMover+FastRelax protocol was found to produce plausible local variation in sampling more effectively than either Mover alone, while still yielding low-energy structures expected of a high-affinity protein complex. Two-body interaction energies were computed using the InteractionEnergyMetric, which includes through-space terms including dispersion, solvation, electrostatic, and hydrogen bonding interactions. Contacts were defined as any residue that has ≤ -0.6 REU interaction energy to at least one individual residue on the antigen side. Per-residue values were written to the B-factor columns and used for visualization. All other visualized structures were folded directly from the seed or design sequences using ABodyBuilder2 and saved with refinement.

4.2 Engineering infrastructure

4.2.1 Data engineering

Our data backend serves as an intermediary connecting functional assay data curated by scientists, direct instrument access, as well as data drawn from public and proprietary databases. In the context of LitL, this constitutes the retrieval and processing of assay data to enable retraining and validation of our models. At a high level, we implemented abstractions for periodic (i) access, (ii) retrieval, and (iii) transformation of data to produce and update core datasets. Together this enables database agnostic deployable pipeline orchestration that persists dataset artifacts in the cloud, providing a common setting in which data from disparate sources may be jointly queried, combined, quality controlled, and ultimately packaged into ML-ready datasets.

In addition to basic data integrity, reproducibility, and versioning carried out automatically by data pipelines, quality control standardizes assay registration and data capture. We set protocols for instrument runs, machine data capture, as well as the application of human and heuristic annotation. As a result of these efforts, we have dramatically increased available data across many more features and with sufficient assay context to drive model improvement.

Designed sequence libraries are verified and registered in the internal large molecule registration system, and each sequence receives a unique identifier. Protein production requests at a scale of 1 ml are submitted via an internal protein production system, and all related request and fulfillment metadata are collected into databases and linked with unique identifiers from the registration system. Subsequent functional assays are recorded in a structured fashion via an internal Lab Information Management System (LIMS) that also supports plating provenance and registrations across all manual and automated Antibody Engineering workflows. Data for each molecule is centralized and integrated into a single repository (Supplementary Figure A9) and made available for consumption by downstream machine learning workflows.

4.3 Design submission

When a design is submitted, metrics to quantify binding affinity and expression yield predictions are computed. Litl is orchestrated using a Kubernetes-based computation pipeline, providing a structured and modular approach to pipeline development. The frontend user interface manages instructions for file submission, file upload to persistent storage, and visualizations of the uploaded antibody data. Alternatively, a Python client can be used for programmatic submission and retrieval of pipeline results. Following file upload, the server performs data formatting checks and triggers the computation pipeline, which executes antibody registration, quality checks, enumeration, folding, inference with property prediction models, out-of-distribution checks, and quality control filtering. Parallel execution is employed for independent tasks. Processed data undergo additional quality control before being passed to the ranking pipeline, using an active learning framework. The selection of the best candidate designs is then passed into an automated visualization tool and a formatting step for DNA synthesis order.

4.4 Experimental methods

Experimental protocols follow Hsiao *et al.* [4, 61] and Wu *et al.* [35]. The methods are described here for convenience.

4.4.1 Immunization

We follow the animal immunization procedure described in Hsiao et al. [4]. Animals were immunized and both splenocytes and lymph node cells were used for hybridoma fusion. RNeasy Mini Kit (Qiagen) was used for total RNA extraction from hybridoma cells. Reverse-transcription (RT) PCR of heavy and light chains was done with a SMARTer RACE cDNA Amplification Kit (Clontech). The forward Universal Primer Mix from SMARTer RACE cDNA Amplification Kit was used for the PCR step. The dideoxy sequencing method was used to directly sequence amplified PCR products.

4.4.2 Repertoire sequencing and mining

Direct lysis with ammonium chloride was used to remove red blood cells. Spleen and bone marrow cells were also collected. Buffer RLT (Qiagen) was used to lyse remaining splenocytes and bone marrow cells. The RNeasy Mini Kit was used to purify RNA

according to the instructions from the manufacturer. Amplicons were purified from agarose gels and sequenced with an Illumina MiSeq instrument. Sequences were processed to 1) extract sequences within variable region boundaries, 2) remove incomplete sequences and sequences with ambiguous residues, 3) remove the first eight residues of framework region 1 (FR1) encoded by amplification primers, 4) extract sequences matching mAb CDR3 length and identity threshold of 57% for CDR H3 sequences, and 5) identify and count unique variable region sequences [4].

To compare against design libraries from generative models, some heavy chain variants of seeds (with light chain fixed) were either chosen directly from the bulk NGS data or designed based on observed patterns in the neighborhood of the seed sequences. First, we collected all sequences that have the same lengths as seeds and are within 12 Hamming distance over the entire variable region and 3 Hamming distance in CDR-H3 from the seeds. Among these, we picked several observed sequences that are most distant by Hamming distance from inferred germline sequences associated with seed sequences. Next, we used the collected sequences to construct Position Specific Scoring Matrix (PSSM) including each seed and their neighbors. We then designed one sequence per seed by sampling the frequency mode of the PSSM at each position while preventing reversion to inferred germline sequence residues associated with the seed. We also included observed sequences that rank high according to the PSSM (i.e. sum of frequencies of observed residues).

4.4.3 Plasmid construction and antibody production

All antibodies were expressed utilizing GLFs as previously described [35]. Briefly, VH and VL fragments were synthesized with 40bp overhang sequences on both sides (Twist Bioscience) and subsequently integrated via Gibson assembly into in-house designed pRK5 expression vectors containing the appropriate heavy chain or light chain constant regions and other elements required for expression (promoter, ORF, poly-A tail) [62]. The product of this reaction was used as the template for GLF amplification, with primers located back-to-back in the noncoding region of the vector, amplifying the whole vector-sized linear DNA insert. This insert contains 2kb extra sequence on each side of the expression cassette, offering extra protection from degradation.

1mL scale IgG expressions were transiently conducted in Expi293F cells (ThermoFisher Scientific). Cells were transfected using PEIpro (PolyPlus PEIpro, Reference #: 115-01L. 1mg/ml). 1µL PEIpro was diluted into 100µL serum-free medium, then 6µL of GLFs (1:1 mixture of heavy chain and light chain, approximate concentration 200µg/µL) were added and incubated for 10 min. The PEI-DNA complex was added to the 0.85ml cells, and cells were cultured in a 96-deep well plate at 37 °C and 8% CO2 for 7 days, with 150µL fresh medium added 24hr post transfection.

The supernatant was collected and purified with a 1-step purification using Protein A affinity resin (MabSelect SuRe™, Cytiva). Quality control of antibody purity was determined by SDS-PAGE with Coomassie blue staining and A280 absorbance to measure protein concentration.

4.4.4 SPR affinity characterization

Surface Plasmon Resonance (SPR) was performed on a Biacore 8K+ (Cytiva). The instrument was primed with HBS-EP buffer (0.01 M HEPES pH 7.4, 0.15 M NaCl, 3 mM EDTA, 0.005% v/v Surfactant P20), and antigens or antibodies were also diluted into the same buffer for all SPR experiments. A Protein A chip was used for antibody capture in all experiments. Experiments were either done using single cycle kinetics (the antigen series successively injected from low to high concentrations, followed by one dissociation step) or multi cycle kinetics (each cycle using one antigen concentration for association followed by a dissociation step, and then repeated for each antigen concentration). In a typical experiment, five concentrations (0.16nM, 0.8nM, 4nM, 20nM and 100nM) for 180s association time, 600s dissociation time with a Flow rate of 30 µl/min. All data were analyzed using Biacore Insight software using a 1:1 binding model.

4.4.5 BV ELISA

BV ELISA was performed following [38], using chimeric mouse/human IgG1 antibodies. Antibodies were purified by protein A affinity chromatography and SEC. BV ELISA is an assay based on ELISA detection of non-specific binders to baculovirus (BV) particles. BV ELISA identifies antibodies that have an increased risk for poor pharmacokinetic properties (fast clearance). Molecules with a BV ELISA score > 1.0 indicate an increased risk. We train a surrogate model by fine-tuning a pre-trained LBSTER [51] protein language model on an internally generated dataset of 2,305 BV ELISA measurements.

4.4.6 Protein expression, purification, and structure determination

The Fab constructs were transfected into CHO cells at a 1:2 (HC:LC) DNA ratio, and expressed for 10 days. After harvesting, the supernatant was collected for purification using GammaBind Plus Sepharose (Cytiva) followed by size exclusion or SP cation exchange chromatography. The purified Fabs were formulated in 20mM histidine acetate pH 5.5, 150mM sodium chloride.

The Fabs were concentrated to 10mg/mL and crystallized by vapor diffusion as follows: 9MVJ: 2.0 M Ammonium sulfate, 0.2 M Sodium chloride, 0.1 M Sodium cacodylate pH 6.5; 9MUZ: 0.2 M Sodium Potassium phosphate, 20% v/v Polyethylene glycol 3350; 9MUY: 0.1 M Ammonium acetate, 0.1 M Zinc chloride, 0.1 M Bis-Tris pH 7.2, 15% v/v PEG Smear High; 9MZC: 0.09 M NPS, 0.1 M BS1 pH6.5, 50% v/v, PM2 (Polymer); 9MZV: 0.2 M Calcium chloride, 0.1 M Tris-HCl pH 8.5, 20% w/v PEG 4000; 9N2V: 0.2 M Sodium chloride, 0.1 M Imidazole pH 8.0, 0.4 M NaH_2PO_4, 1.6 M K_2HPO_4; 9N7M: 0.2 M Ammonium sulfate, 0.1M MES pH 6.5, 30% w/v PEG 5000 MME; 9N7O: 0.1 M Bis-Tris propane pH 9.0, 10% v/v PEG 200, 18% w/v PEG 8000;

Crystals were cryoprotected by addition of ethylene glycol. Data were collected at synchrotron sources, as indicated in Supplementary Table A2, and data were scaled using XDS [63]. The structures were determined by molecular replacement, using PHASER [64], and the models were built in COOT [65] and subsequently refined

in PHENIX [66] to final statistics presented in Supplementary Table A2. The simulated annealing omit difference electron density maps (Supplementary Figure A11) demonstrate the fidelity of the final models with the electron density.

Supplementary information Supplementary files accompany this article.

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Declarations

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Competing interests

All authors are or were employees of Genentech Inc. (a member of the Roche Group) or Roche, and may hold Roche stock or related interests.

Ethics approval

All animal studies were performed in animal facilities accredited by the Association for Assessment and Accreditation of Laboratory Animal Care International. The procedures for animal studies were compliant under the Institutional Animal Care and Use Committee of the facility.

Availability of data and materials

LBSTER models were trained using the UniRef50, PDB, and Observed Antibody Space databases. All other models were trained on internally generated datasets described in the experimental methods, Section 4.4.

Crystallographic coordinates and data were deposited at the RCSB with accession codes 9MUY, 9MUZ, 9MVJ, 9MZC, 9MZV, 9N2V, 9N7M, 9N7O.

Code availability

Discrete Walk-Jump Sampling, PropEn, LBSTER, and Cortex are available on the Prescient Design GitHub. DyAb is available as a model within LBSTER. The Prescient standard library (Beignet) and LaMBO-2 are available on GitHub.

Authors' contributions

R.G.A., D.B., R.B., K.C., H.D., N.C.F., V.G., I.H., R.K., S.K., J.R.K., J.T.K., J.LV., J.H.L., A.L., S.R., F.S., S.D.S., and A.M.W. conceived of and designed the work. R.A., J.B., T.B., P.C., T.D., H.D., A.D., J.F., N.C.F., V.G., A.G., J.H., H.I., A.I., S.J., S.K., M.K., J.K., J.L.V., A.L.F., E.L., W.C.L., J.Y.Y.L., S.P.M., E.M., S.N., J.W.P., J.P., S.R., F.S., S.D.S., N.T., H.T., A.W., A.M.W., B.W., S.W., and K.Z. acquired the data. R.A., D.B., J.B., T.B., P.C., A.C., T.D., H.D., N.C.F., V.G., A.G., I.H., H.I., T.J., S.K., J.R.K., J.K., J.L.F., J.H.L., E.L., D.L., W.C.L., A.L., J.L., O.M., E.M., K.M., H.M.P., J.P., S.R., S.R., F.S., I.S., A.S., S.D.S., E.W., A.W., A.M.W., B.W., and K.Z. analyzed and interpreted the data. R.A., D.B., T.B., H.D., N.C.F., V.G., A.G., J.H., H.I., A.I., S.K., M.K., J.K., A.L.F., E.L., J.Y.Y.L., A.L., J.L., S.P.M., O.M., S.N., J.W.P., J.P., S.R., S.S., S.D.S., N.T., E.W., A.M.W., and K.Z. created methods and algorithms presented in this work. R.A., R.B., K.C., A.D., J.F., N.C.F., V.G., J.H., I.H., S.J., T.J., R.K., S.K., J.R.K., J.T.K., J.L.F., J.H.L., A.L., E.M., J.M., K.M., H.M.P., J.W.P., S.R., A.R., S.R., S.S., I.S., S.D.S., N.T., A.W., A.M.W., and Y.W. wrote and edited the manuscript. R.B., P.C., K.C., H.D., V.G., I.H., R.K., S.K., J.R.K., J.T.K., J.L.V., A.L., J.M., S.R., A.R., F.S., A.M.W., B.W., and Y.W. supervised the research. All authors discussed the results and approved the final version of the manuscript.

Appendix

A Supplementary data

Table A1: SPR binding kinetics for select antibody designs reported in the main paper. Full antibody and antigen sequences and additional data, including goodness of fit metrics, are available in the Extended Data.

Antibody Alias	k_a (1/Ms)	k_d (1/s)	K_D (M)	pKD	Target
EGFR-P01451	5.29e+06	4.50e-04	8.50e-11	1.01e+01	EGFR
EGFR-P01484	4.12e+06	6.16e-04	1.50e-10	9.82e+00	EGFR
EGFR-P01503	3.99e+06	6.06e-04	1.52e-10	9.82e+00	EGFR
EGFR-P01519	2.16e+06	1.44e-02	6.68e-09	8.18e+00	EGFR
EGFR-P01606	3.64e+06	5.96e-04	1.64e-10	9.79e+00	EGFR
ERBB2-P00873	1.20e+05	2.01e-04	1.67e-09	8.78e+00	ERBB2
ERBB2-P00961	1.25e+05	3.14e-04	2.52e-09	8.60e+00	ERBB2
ERBB2-P00965	1.22e+05	2.68e-04	2.20e-09	8.66e+00	ERBB2
IL6-P01545	1.27e+06	1.17e-03	9.18e-10	9.04e+00	IL6
IL6-P01548	8.70e+05	8.18e-04	9.41e-10	9.03e+00	IL6
IL6-P01573	2.20e+06	1.19e-03	5.40e-10	9.27e+00	IL6
IL6-P01577	1.13e+06	1.50e-03	1.33e-09	8.88e+00	IL6
IL6-P01615	6.59e+05	9.64e-04	1.46e-09	8.84e+00	IL6
IL6-P01634	5.82e+05	3.53e-04	6.07e-10	9.22e+00	IL6
IL6-P01662	9.76e+05	1.37e-03	1.41e-09	8.85e+00	IL6
IL6-P01770	1.16e+06	1.11e-03	9.61e-10	9.02e+00	IL6
OSM-P01123	1.13e+06	1.83e-03	1.61e-09	8.79e+00	OSM
OSM-P01250	6.64e+05	3.55e-04	5.34e-10	9.27e+00	OSM
OSM-P01344	3.67e+05	3.55e-04	9.67e-10	9.01e+00	OSM
OSM-P01377	1.04e+06	1.72e-03	1.66e-09	8.78e+00	OSM
OSM-P01473	3.31e+05	2.69e-04	8.12e-10	9.09e+00	OSM
OSM-P01508	1.30e+05	3.32e-04	2.55e-09	8.59e+00	OSM
OSM-P01568	8.67e+04	6.60e-04	7.61e-09	8.12e+00	OSM

Table A2: Crystallographic data

PDB code	9MVJ	9MUZ	9MUY	9MZC
X-ray source	NSRRC TPS 05A	SSRF BL02U1	Diamond I03	SSRF BL02U1
Wavelength (Å)	0.99987	0.97918	0.97625	0.97918
Detector	Rayonix MX300HS	Eiger2 S 9M	Eiger2 XE 16M	Eiger2 S 9M
Resolution range (Å)	49.3 – 1.95	147.3 – 1.71	50.9 – 1.97	47.5 – 1.58
Highest res. bin (Å)	2.00 – 1.95	1.74 – 1.71	2.02 –1.97	1.60 – 1.58
Space group	$H3_2$	$P2_12_12$	C_2	$P2_12_12$
Multiplicity	20.7, 21.2	7.0, 6.0	6.9, 6.6	6.9, 7.1
Complete (%)	100, 100	100, 100	99.9, 99.8	98.1, 95.1
Mean I/σ_I	21.0, 2.5	11.3, 1.9	13.3, 2.2	12.4, 2.0
Wilson B ($Å^2$)	33.8	19.6	32.1	3.5
CC ½ (highest bin)	0.86	0.69	0.87	0.69
Rmerge (%)	10.7, 159	10.8, 86.1	7.7, 80.9	16.7, 107
# reflections (Rfree set)	59,055 (5,735)	91,776 (8,797)	38,938 (3,770)	62,385 (3,054)
Resolution range (Å)	39.7 – 1.95	73.7 – 1.71	33.3 – 1.97	47.3 – 1.58
Rwork, Rfree (%)	18.0, 19.8	16.6, 19.6	20.8, 22.3	17.5, 20.2
# non-H atoms	3,715	7,682	3,585	4,264
# solvent molecules	328	939	225	606
Rmsd bond lengths (Å)	0.004	0.004	0.005	0.006
Rmsd bond angles (°)	0.668	0.644	0.832	0.913
Ramachandran fav. (%)	97.4	98.1	96.5	97.9
Ramachand. outlier (%)	0	0	0.24	0
Ave B-factor ($Å^2$)	48.2	23.3	53.9	12.6
Molprobity clash score	1.82	1.43	3.97	1.67

PDB code	9MZV	9N2V	9N7M	9N7O
X-ray source	PETRAIII P11	PETRAIII P11	SSRF BL02U1	SSRF BL02U1
Wavelength (Å)	1.03321	1.03321	0.97918	0.97918
Detector	EIGER2 X 16M	EIGER2 X 16M	Eiger2 S 9M	Eiger2 S 9M
Resolution range (Å)	48.3 – 1.90	46.55 – 1.97	46.53 – 2.15	44.9 – 1.48
Highest res. bin (Å)	1.94 – 1.90	2.00 – 1.97	2.20 – 2.15	1.50 – 1.48
Space group	$P2_1$	$P4_1$	$P4_1$	$P4_12_12$
Multiplicity	6.9, 6.9	13.7, 13.4	5.1, 4.2	26.1, 21.1
Complete (%)	99.3, 99.1	99.5, 100	99.9, 100	99.8, 100
Mean I/σ_I	12.4, 2.2	16.1, 2.1	7.7, 2.0	13.0, 2.0
Wilson B ($Å^2$)	20.6	27.8	19.0	19.6
CC ½ (highest bin)	0.68	0.745	0.154	0.306
Rmerge (%)	13.4, 103	15.4, 162	22.4, 70.7	18.2, 184
# reflections (Rfree set)	71,330 (3,484)	95,351 (4,880)	73,985 (3,682)	94,027 (4,649)
Resolution range (Å)	48.3 – 1.90	46.6 – 1.97	41.3 – 2.15	31.8 – 1.48
Rwork, Rfree (%)	17.7, 21.4	17.4, 20.2	21.0, 24.2	17.2, 20.5
# non-H atoms	7,507	7,635	7,474	3,500
# solvent molecules	839	853	826	601
Rmsd bond lengths (Å)	0.002	0.002	0.002	0.006
Rmsd bond angles (°)	0.591	0.589	0.512	0.841
Ramachandran fav. (%)	98.0	98.0	98.1	97.7
Ramachand. outlier (%)	0	0	0	0
Ave B-factor ($Å^2$)	24.0	38.0	27.5	26.1
Molprobity clash score	0.92	0.82	1.15	1.29

Table A3: SPR binding kinetics for designs reported in Figure 4. Full antibody and antigen sequences and additional data, including goodness of fit metrics, are available in the Extended Data. ΔpKD values are reported for measurements where design and seed were on the same plate, leading to two slightly different affinities for the OSM-N021 seed. "N/A" PDBIDs are the two folded anti-HER2 designs for which experimental structures were not obtained. Affinities for 9MSW and 9MU1 were previously reported in [32].

PDBID	Antibody Alias	k_a (1/Ms)	k_d (1/s)	K_D (M)	pKD	Seed pKD	Δ pKD
9MVJ	EGFR-P01451	4.86E+06	6.24E-04	1.28E-10	9.891	8.517	1.374
9MSW	EGFR-P01550	4.60E+06	5.65E-04	1.23E-10	9.911	8.517	1.394
9N7M	OSM-P01295	2.78E+05	1.30E-04	4.68E-10	9.330	8.770	0.560
9N7O	OSM-P01513	3.26E+05	1.41E-04	4.33E-10	9.364	8.708	0.656
9MUZ	IL6-P01770	1.67E+06	1.03E-03	6.17E-10	9.210	7.686	1.524
9MUY	IL6-P01634	1.14E+06	3.03E-04	2.66E-10	9.575	8.266	1.309
N/A	ERBB2-P00873	1.28E+05	1.67E-04	1.30E-09	8.884	8.195	0.689
N/A	ERBB2-P00965	1.39E+05	2.04E-04	1.47E-09	8.833	8.195	0.638

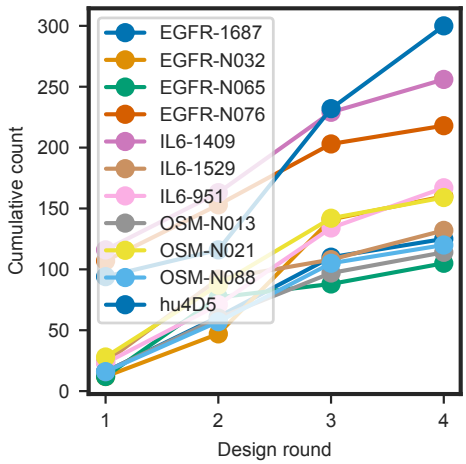

Fig. A1: Cumulative number of labeled (expression yield and binding affinity) designs in the neighborhood of each seed (<= 16 edit distance) over rounds

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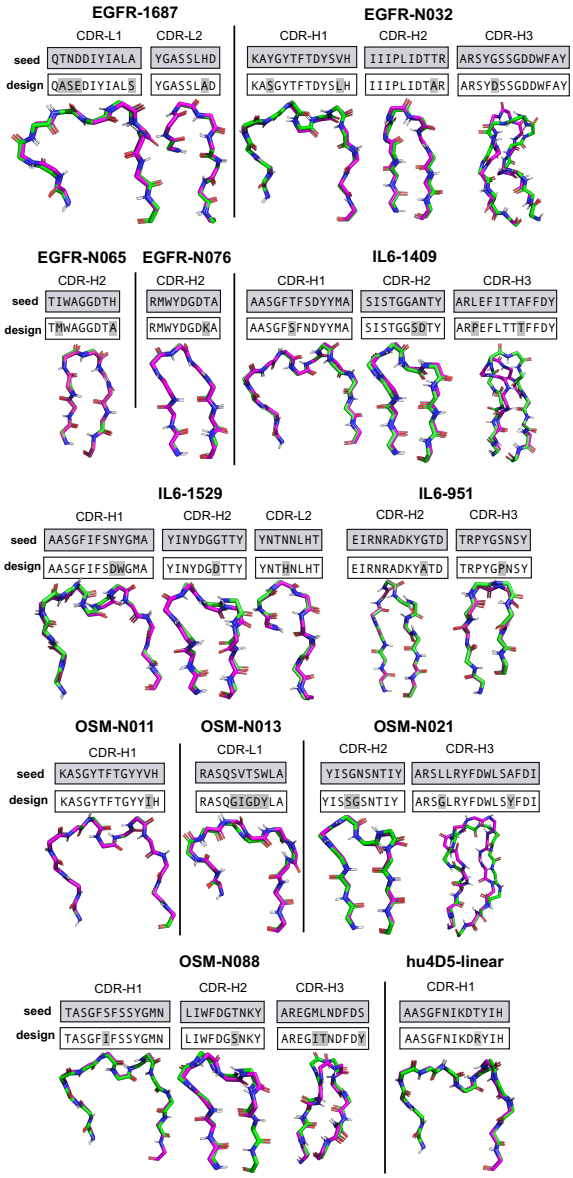


Fig. A2: CDR loop comparison between seeds and designs. Global alignment of seed (green) and affinity matured designs (magenta). All CDR loops (AHo definitions [44]) containing mutations between seed and design are shown (other mutations may be present in non-CDR regions).

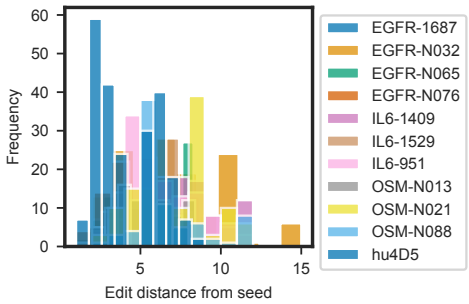


Fig. A3: Histogram of edit distances of all binding designs with respect to their respective seed sequences. Edit distances range from 1 to 14.

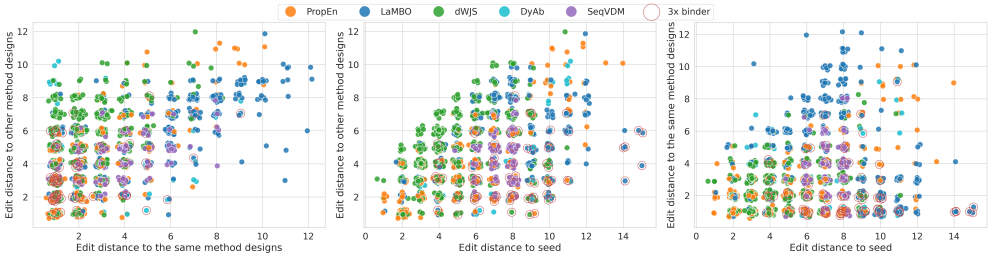


Fig. A4: Edit distances of generated designs to seed, other method designs, and other designs from the same method. It can be seen that 3x binders usually have lower edit distance to both, other method designs and other designs from the same method, but higher edit distance to seed. This highlights the importance of our multi-round setup, that allows us to drift further away from the starting seed. It is also worth noting, that while most methods have rather linear relationship between distance to seed and distance to other method designs, with a slightly higher similarity to other method designs, dWJS can produce tangent designs as shown by low edit distance to seed and high edit distance to designs from other methods.

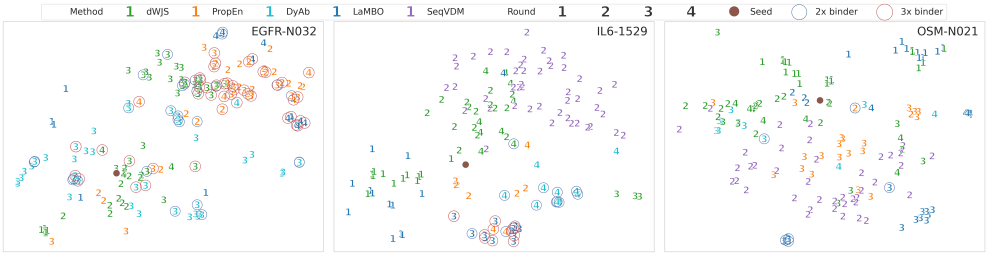


Fig. A5: t-SNE[67] plot of ESM-2 [52] embeddings of designs around 3 selected seeds. We can see that dWJS and SeqVDM, as expected, explore the design space more widely, while designs of PropEn and LaMBO are more localized, especially within the same round. The importance of thoroughly exploring the space around the seed is also highlighted by the fact, that most of the time 2x and 3x binders are tightly grouped and can be far from the seed.

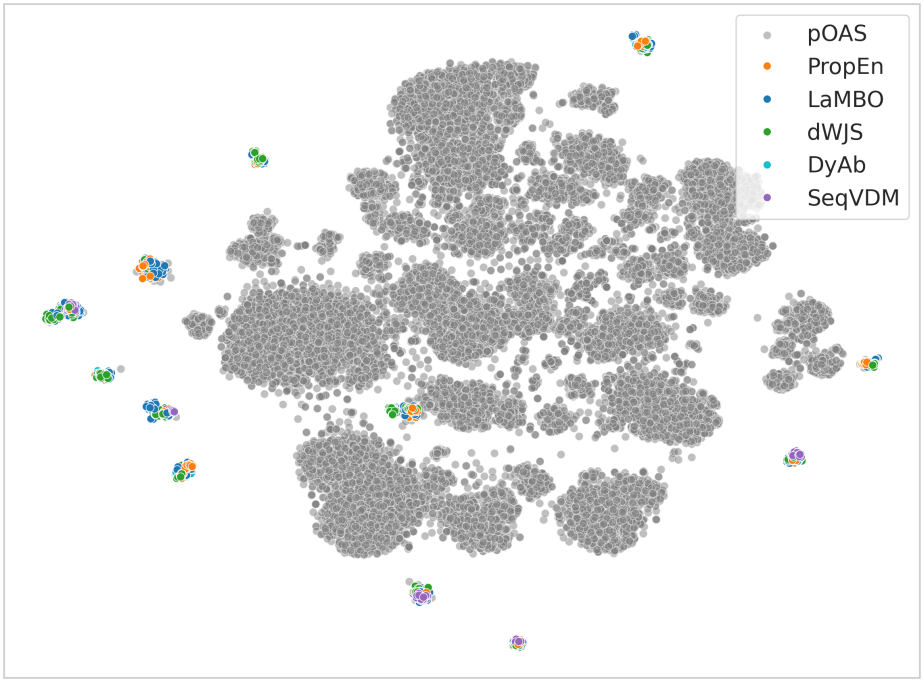


Fig. A6: t-SNE[67] plot of ESM-2 [52] embeddings of designs for all seeds plotted against paired OAS [55] (30k random sub-sample). Our seeds are mainly either on the fringes of this reference distribution or are completely OOD.

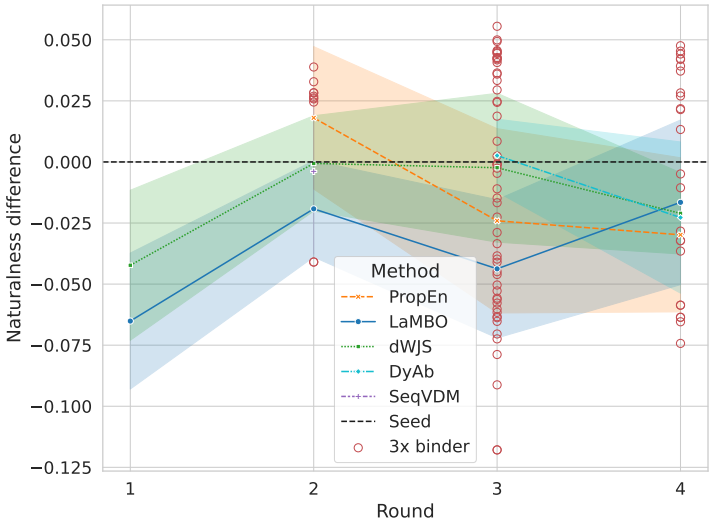


Fig. A7: Naturalness score [68] (inverse perplexity of AntiBERTy PLM [19]) of the designs over the different rounds. Higher naturalness signifies that the language model deems the sequence to be likely, w.r.t it's training data. We can see that as number of 3x binders increases going from round 2 to 3 or 4 the naturalness generally decreases. This signifies that as the designs are improving they are drifting slightly away from a naive antibody distribution.

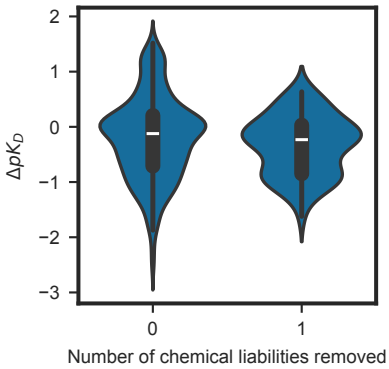


Fig. A8: Change in pK_D versus number of chemical liabilities removed from a seed sequence.

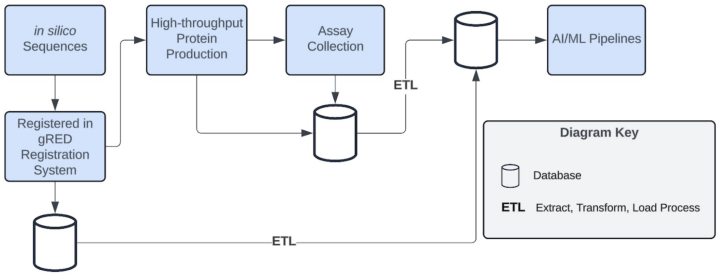


Fig. A9: Diagram of extract, transform, load process for data pipelines.

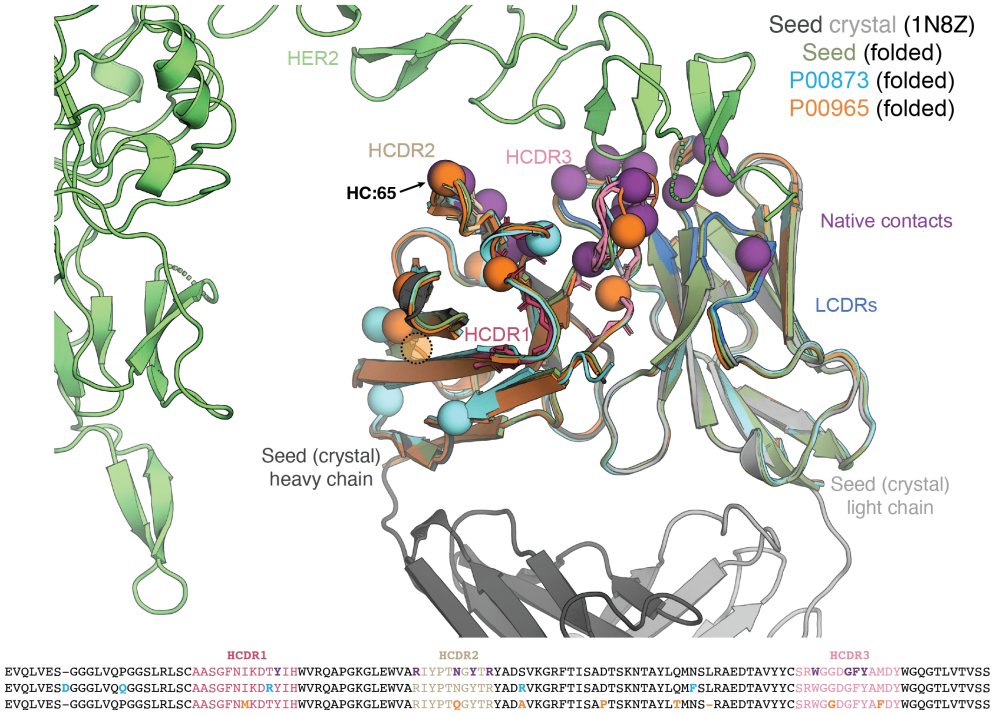


Fig. A10: Zoom-out of the Trastuzumab (hu4D5-linear)-HER2 complex crystal structure (PDBID: 1N8Z) with heavy/light chain colored in dark/light gray, HCDRs colored as in Fig 4, LCDRs in dark blue, native contacts in purple, with folded Fv structures (ABodyBuilder2) of the seed (dark green) and two designs (light blue and orange) aligned onto the crystal. A dashed transparent circle depicts the approximate location of the deletion in P00965. The folded structures exhibit very close similarities in all loops except for minor variability in HCDR3, indicating that the sequence changes are unlikely to have introduced dramatic structural rearrangements. Note that position 65 on the heavy chain (HC:65) is the only native seed contact that is directly mutated (in P00965 only). All other mutations are orthogonal to native contacts, with most localized to the framework region. The complete heavy-chain sequences for the seed and two designs are shown at bottom and color-coded by origin. There were no edits to the light chain in either of these two designs.

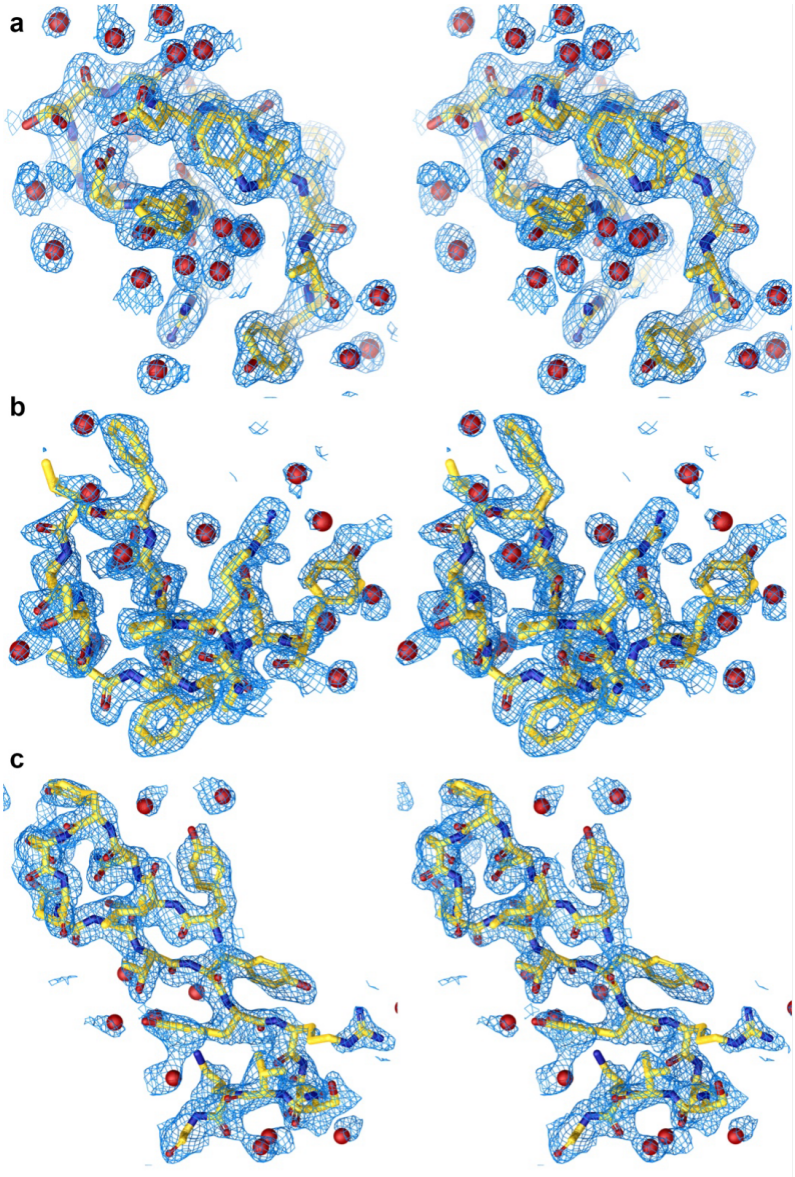
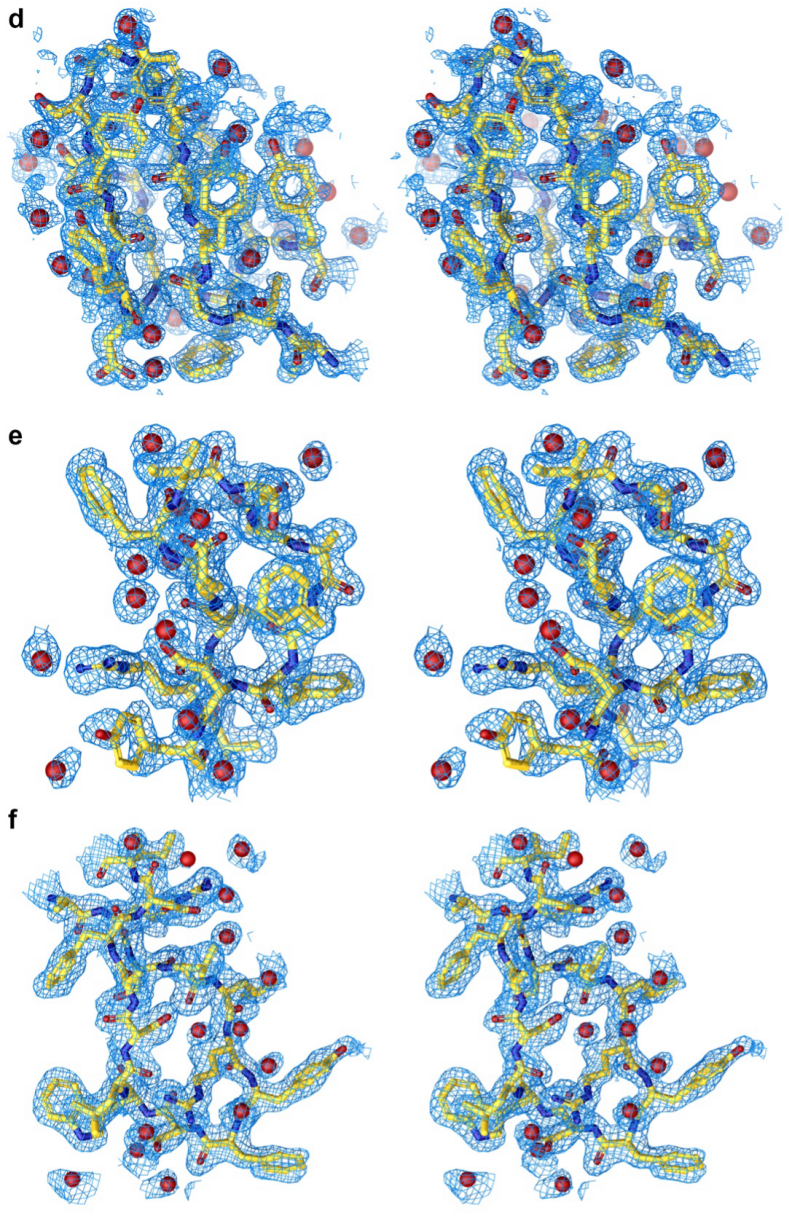


Fig. A11: Electron density maps. Divergent eye stereo images of the simulated annealing composite omit difference electron density maps, (2m$|F_o|$-D$|F_c|$) exp(iαc), CDR H3 of Fabs **a** 9MVJ, **b** 9MUZ, **c** 9MUY (CDR H2), **d** 9MZC, **e** 9MZV, **f** 9N2V, **g** 9N7M, and **h** 9N7O, contoured at 1σ.



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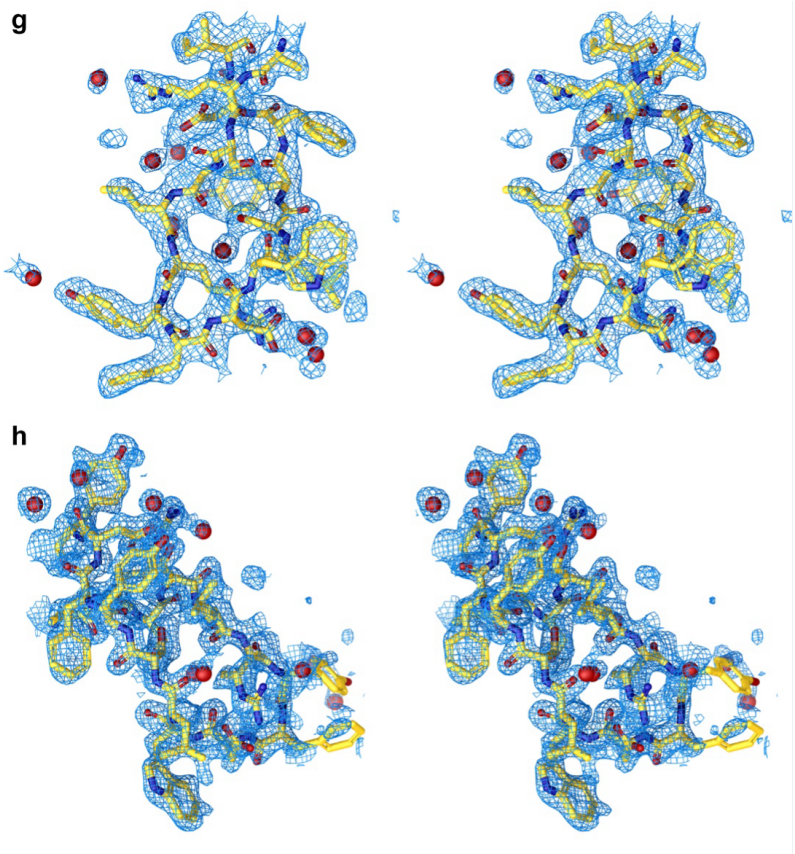

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