



Agent-Based Modeling: A Systematic Assessment of Uses and Requirements for Enhancing Pharmaceutical Research and Development Productivity

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39 Abstract
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41 A crisis continues to brew within the pharmaceutical research and development (R&D)
42 enterprise: productivity continues declining as costs rise, despite ongoing, often dramatic
43 scientific and technical advances. To reverse the trend, various suggestions are being offered for
44 both the expansion and broader adoption of modeling and simulation (M&S) methods. These
45 suggestions are strategies and scenarios intended to enable new M&S uses that directly engage
46 R&D knowledge generation and build actionable mechanistic insight, thereby opening the door to
47 enhanced productivity. What M&S requirements must be satisfied to access and open the door,
48 and begin reversing the productivity decline? Can current methods and tools fulfill the
49 requirements, or are new methods necessary? We provide and explore answers. In so doing, we
50 identify essential, key roles for agent-based and other methods. We assemble a list of
51 requirements necessary for M&S to meet the diverse needs distilled from a collection of research,
52 review, and opinion articles. We argue that to realize its full potential, M&S should be actualized
53 within a larger information technology framework, a dynamic knowledge repository, wherein
54 models of various types execute, evolve, and increase in accuracy over time. We offer some
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8 details of the issues that must be addressed for such a repository to accrue the capabilities needed
9 to reverse the productivity decline.
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14 Pharmaceutical research and development (R&D) is in the midst of a productivity decline. Unified,
15 transdisciplinary, in silico modeling and simulation (M&S) methods are viewed broadly as a promising
16 countermeasure. Agent-based (AB) modeling is a phrase used currently to identify relatively young
17 modeling methods that utilize software agents. We review and present evidence that AB methods will be
18 essential contributors to successful M&S countermeasures.
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30 The development of agent modeling tools and the availability of increasingly detailed, varied, and
31 abundant data coupled with advances in computation have made possible a growing number of agent-
32 based modeling and simulation (AB M&S) applications across a variety of non-biomedical domains and
33 disciplines. To illustrate, we identify early ¹⁻¹⁵ and more recent ¹⁶⁻³² uses. Macal and North ³³ provide
34 additional examples and a tutorial on AB M&S methods. Within the biomedical domain, AB M&S is a
35 relatively new approach for studying systems composed of interacting components, some of which can be
36 autonomous. The methods are used primarily to gain insight into mechanisms responsible for phenomena
37 of living systems. We cite early ³⁴⁻⁴¹ and more recent ⁴²⁻⁵⁷ examples of such applications. Amigoni and
38 Schiaffonati ⁵⁸, An et al. ⁵⁹, and Edelman et al. ⁶⁰ provide biomedically-focused reviews. Several
39 applications exemplify the expanding variety of uses relevant to the pharmaceutical sciences ^{47,61-73}.
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42 Pharmaceutical science stakeholders agree that there is a crisis within the broad pharmaceutical R&D
43 domain (private and public): productivity continues to decline, even in the face of dramatic scientific and
44 technical advances accompanied by a data deluge, especially at the molecular level. A flurry of recent
45 reviews and commentaries ⁷⁴⁻¹⁰³ discuss the problems from several different perspectives and offer
46 strategies and scenarios for how M&S methods can and are being used to enhance productivity. The
47 different perspectives include pharmacometrics (including translational and physiologically based
48 pharmacokinetics–pharmacodynamics (PBPK), and disease progression M&S), quantitative and systems
49 pharmacology, and model-based drug development. Given the apparent fit between designed uses of AB
50 M&S methods and the multifarious problems cited in the reviews that can benefit from computational
51 M&S methods, it is surprising that only two of the citations mention AB M&S methods. No examples
52 are presented within those citations of any current use of AB M&S methods within pharmaceutical
53 companies. Does that situation signal ripe opportunity for AB M&S methods to add new value beyond
54 that delivered using the established methods? That question, although provocative, is premature because
55 one should not try to force-fit a particular M&S method to a particular set of problems. We should first
56 evaluate where and how the cited domain experts envision M&S methods being used to reverse the
57 productivity trend.
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60 The cited experts anticipate shifting focus from analysis of data to discovery and challenge of explanatory
61 mechanisms. They see M&S becoming integral and essential to envisioned discovery and development
62 processes that are dramatically more productive in part because of improvements in use of M&S methods
63 across all R&D activities. Yet they also make clear that the established practice is to select one or more
64 modeling tools, drawn primarily from those already in use, to address the particular problem at hand. The
65 practice is the same independent of stage in the R&D process. Various scientists, often separated in time
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and space across R&D processes, integrate the derived information. Anticipating that having M&S integrated across R&D activities can improve productivity, what new demands are placed on M&S methods? We show why multifaceted, networked M&S uses require drawing from an expanded computational modeling method and tool repertoire. Can current methods and tools fulfill the requirements? No. We justify that answer and discuss why AB M&S methods are essential. It becomes clear that an analog (see Definitions sidebar) based knowledge repository will be needed. We identify the M&S method requirements, and that brings into focus additional M&S uses that we believe the repository's framework will likely need to enable.

14 15 16 17 18 19 20 21 22 23 24 **Definitions** 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60

actor: an entity identifiable by an observer as a cause of an effect; an entity that participates in a process (plays a part); in computer science it is a mathematical model of computation that treats *actors* as the universal primitives: in response to a received message, an actor can make local decisions, create more actors, send messages, and determine how to respond to the next message received.

agent: a software object that can schedule its own events (within an analogue, it is quasi-autonomous); it senses and is part of its environment; it pursues and can revise an agenda within a larger script; some of its attributes and actions may be designed to represent biological counterparts, whereas others will deal with issues of software execution

agent-based: something formulated with or built up from agents; in this context, it identifies a simulation model designed in which quasi-autonomous agents are key components. Terms that are often synonymous within the M&S literature include individual-based, multi-agent.,

framework: a carefully crafted assemblage of tools, devices (some software, some hardware, and occasionally even some wet-ware), usage protocols, good practices, etc., governed by a set of component interoperability standards. Upon satisfying the Paramount uses and the listed requirements, we expect the framework to be an extensible, distributed, open, loosely coupled (yet unified from the users perspective),

analog: a software device that has (some) aspects and attributes that are similar to those of its R&D referent, which exists and can operate in isolation and in the absence of its R&D counterpart; in biomedical M&S, a model implemented in software that, when executed, produces phenomena that mimic one or more measured or attributes observed during referent wet-lab experiments. In this context, most analogs will be suitable for experimentation.

in silico experiment: it is precisely analogous to a wet-lab experiment. An analog is a hypothesis: the mechanism produced upon execution by interacting components will result in phenomena, often at different scales, that are similar, or not, to prespecified wet-lab phenomena. Measurement of features during execution enables testing the hypothesis. That activity is an in silico experiment.

analog based knowledge repository: easily accessible, organized framework feature. Its content is an up-to-date instantiation of all accumulated, new, and proprietary, project related mechanistic knowledge in an accessible, easily understood, observable, and interactive form. It contains annotated records of analogs (current and falsified), their mechanisms, how they were composed plus the rationale, along with records of in silico experiments. All Paramount uses can be conducted using the analog based knowledge repository. We envision domain experts making go/no-go decisions after interactive exploration of many scenarios (simulations) within the repository.

MODELING, SIMULATION AND THE PRODUCTIVITY CRISIS

Ideally, one should begin any M&S project without bias for any particular model types or methods¹⁰⁴. The first task is to clearly identify near and longer term expectations. Among the questions to be answered are these: what are the problems? What questions need to be answered? What new knowledge is sought and how will it be used? What decisions must be made? When are the deadlines? What

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resources are available? Etc. Within pharmaceutical R&D, these questions are complicated by the nested, networked, multi-year, evolving nature of the overall enterprise. Scientific insight achieved at an early stage may be critical downstream, during dose ranging studies or clinical trials, for example, and early planning for that prospect may influence selection of M&S methods in important ways. Yao et al.¹⁰³ illustrate the variety of relationships and common computational methods that support them (see Supplemental Fig. S1).

Consider a model and method judged appropriate for a particular discovery or early development problem. The insight sought is intended to be useful for downstream as well as for current decision-making. Can the model, method, and information be easily utilized as needed within a tight time window at a downstream go/no-go decision juncture? If doing so proves problematic because of differences in models, methods, tools, etc., uncertainties and delays increase unnecessarily along with the risk of a flawed decision. The situation is complicated further by a larger, pressing, overarching need: reverse the declining trend in productivity.

The cited experts make the case that M&S methods are essential to simultaneously increasing productivity of therapeutic drug development, and facilitating the recursive cycle of new knowledge buildup aimed at improved quality care. Accepting that position, we view the enterprise as a networked, experiment-intensive system that begins small (significantly left on the Systems Information scale in Fig. 1). As R&D progresses, the system evolves and expands: i.e., for a particular aspect of the system, its location on the Systems Information scale in Fig. 1 inches to the right, which becomes a large, distributed, multiscale, multi-aspect M&S challenge. In what variety of ways do the cited experts envision M&S methods being used? Answers are provided in Supplement–Uses; a sample of answers is provided in the Sidebar. Given those particular uses, we propose a set of Paramount uses, and then present five requirements, which we argue must be satisfied to enable achieving those uses efficiently. We discuss M&S methods that will enable a unified M&S approach to satisfy those requirements. To our knowledge, such an analysis has not been done. We argue that such an examination is necessary and essential to discover strategies capable of restoring and enhancing productivity.

KNOWLEDGE INTEGRATION

Knowledge integration is an essential, Paramount use. For this discussion, we limit attention to knowledge relevant to the primary R&D project focus: the particular disease, morbidity, or health issue, the biologic or chemical entity treatment intervention; the pharmacological, toxicological, and clinical outcomes that are consequences of treatments; and the variety of mechanisms (even when vague) that are offered to explain those phenomena. We ignore other important categories of knowledge that can impact go/no-go decisions, but the approach and framework described below can be expanded to include them. Examples of those categories include regulatory science; chemistry, manufacturing, and control; human resources; accessible contract services; etc.

Although the reviews cited in the Model Uses Sidebar discuss roles of various computational models and methods in knowledge integration, very little knowledge actually resides in those models. The semantics expressing the knowledge is provided manually by the domain experts using their mental models while interpreting the input and output of those models, typically as prose supported by graphics. Today, that activity occurs separate from the computational framework. Much of the mechanistic insight still resides within mental models, and that presents a problem: mental model differences, similarities, and

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inconsistencies are difficult, and often impossible to ascertain. Mental models are subject to their own forms of error introduction and propagation. Increasing reliance on synthetic analogs (defined below) presents advantages because they can evolve into executable representations of what we know (or think we know) about biological systems. Those representations are called executable biological knowledge embodiments^{65,66,105} and dynamic knowledge representations^{34,59,61,62,106-110}. Such executions are suitable for knowledge discovery^{59,109,110}. Knowledge embodiment is made feasible because synthetic analogs provide concrete instances of that knowledge rather than analytic descriptions of conceptual representations. When an analog is executed, it demonstrates when, how, and where our knowledge matches or fails to match details of the referent system.

For current knowledge and beliefs to be useful (especially in a social context like shared model usage, validation, and falsification), it must be embedded in an analog and visible to the user (which is not the case now). That will be the case in the envisioned M&S scenarios because analogs help build schemata for knowledge (and ignorance) representation, which will provide a mechanism for the curation and maintenance of the embedded knowledge. Users are expected to be able to observe different aspects of knowledge in action and do so from different perspectives, as we do with model biological systems. Users must be able to readily identify the knowledge and be able to discuss it, rely on it, dispute it, and falsify it (or not), all while reflecting on how that knowledge impacts the project. To achieve these capabilities, most, if not all, modeling activities and all mechanism representations will need to take place within a framework of the type described in the first sidebar. The R&D project related content of that framework will become part of an interactive, analog based knowledge repository.

It should be noted that knowledge is not currently embedded in the any of the variety of pharmacometric or systems pharmacology models identified for use in the reviews⁷⁴⁻¹⁰³. As documented by An^{106,108} and Hunt et al.^{65,105}, embedding knowledge in pharmacometric and ordinary differential equation (ODE) models is challenging, if not problematic. Equations are typically used to describe patterns in data. To illustrate, restrict attention to ODE models that also describe hypothetical measures taken on idealized, mechanistic models, such as signaling pathways, Michaelis-Menten kinetics, pharmacodynamic models, PBPK models, and mixed effect, population based PK models used in analysis of clinical trial data. The conceptual models associated with these equation-based models do reflect knowledge but it exists separate from the equations. Humans interpreting the input-output (I/O) of the equations use prose and sketches to provide the semantic grounding for those models in terms of both the idealized, conceptual model and knowledge of the referent system. That semantic grounding is done manually, typically outside of the computational tool being used. Hence, neither knowledge nor semantics is *embedded* in those equation models.

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Analog Grounding Issues

Grounding issues must be addressed to satisfy Requirements. Key issues discussed in detail by Hunt et al.¹⁰⁵ are summarized in Supplemental Text. The units, dimensions, and/or objects to which a variable or model constituent refers establish groundings. Absolute grounding: variables, parameters, and I/O are in real-world units. Relational grounding: variables, parameters, and I/O are in units defined by other system components. Relational grounding requires a separate analog-to-referent mapping model. To satisfy Requirements, a spectrum of model classes, methods, and groundings (illustrated in Fig. 1) will be needed: absolute grounding occupies one extreme; relational grounding occupies the other.

Absolute grounding provides simple, interpretive mappings between simulation output, parameter values, and referent data. However, complex issues must be addressed each time one of the following occurs: expand the model to include additional phenomena; combining models; and/or model context changes. Expansions are challenging, even infeasible, when center-left in Fig. 1. Reusability is hindered in part because the conflated semi-mechanistic, equation-based model and the model-to-referent mapping model have different uses.

We expect analogs to evolve (become more complicated) as R&D advances and new mechanistic insight accumulate, which will require changing, adding, and removing component linkages within analogs. We recommend keeping most component groundings relational. So doing facilitates component replacement, limiting any one component formulation solely to its coupling with the others. Any component can be replaced at will as long as the minimal I/O interface requirements are met. Starting with relationally grounded analog components allows the modeler to iterate progressively from qualitative to quantitative validation. .

Management of uncertainty

At project initiation, uncertainty is pervasive. Projects typically begin considerably to the left on the Fig. 1 Uncertainty and System Information scales. Uncertainty sources are varied and plentiful. They need to be identified, annotated, and updated. We focus on uncertainties directly associated with the mechanistic theories on which the project is based. To enable the full set of M&S uses, project scientists must do more than manage uncertainty: an engineered plan for reducing it systematically is required. For the sake of discussion, imagine that the project is successful and that, upon product launch, the project's validated, explanatory, mechanistic knowledge and insight place it at the center of the System Information scale. Project domain experts estimate that it is midway on the Uncertainty scale. R&D efforts expanded the mechanistic knowledge "space" and shrank the "space" of uncertainty and ignorance. We can infer that productivity-enhancing M&S methods must simultaneously facilitate doing the same. Preference must be given to M&S methods that can do both. Reliance on computational models that simply abstract away uncertainties is counterproductive: so doing does yield simple, easily managed models, which is useful at the beginning of a project, but it also adds a new source of uncertainty. The core source of uncertainty is the experimental evidence on which the project's mechanistic theories are based (in the context of all other available knowledge and insight), and we recognize that current theory is just one drawn from a space of possible or plausible mechanistic theories.

Studies conducted by Amgen¹¹¹ and Bayer HealthCare¹¹² found that published, pre-clinical, scientific findings that were important to their R&D efforts could be confirmed in only 11–25% of cases. A rule-of-thumb among early-stage venture capital firms is that at least 50% of published studies, even those in top-tier academic journals, cannot be repeated¹¹³. Consequently, there is significant risk that the evidence supporting the conceptual mechanistic models on which the project is based is flawed. Even when results are repeated, variability can be considerable. Rarely can measurements made on cell culture models be mapped quantitatively 1:1 to comparable measures made on animal models. Similarly, animal model

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phenomena rarely map 1:1 to human counterparts. Hence, there is considerable uncertainty about how results from different experiments can or should be mapped to, and thus influence, the conceptual mechanistic models on which project scientists are relying. Such uncertainty and mapping dilemmas present problems for those using conventional inductive, equation-based models (typically ODEs) of the type discussed in the cited reviews. Modelers understand the issues: when using such methods, they would prefer to be on the far right of Fig. 1. The conventional strategy is to request more data. So doing postpones mechanistic modeling. Unfortunately, it may be necessary for the project to advance beyond the next few go/no-go decision points before the requested data begins to come available. While waiting for the required data, the accepted strategy for dealing with uncertainty issues is to abstract them away: if we make particular simplifying assumptions, we can create an idealized, hypothetical mechanistic scenario that, if validated, will place us on the right side of Fig. 1 where inductive, predictive models can be reliable. In doing so, model-grounding issues, discussed below, are typically ignored. As the project advances, there is no straightforward way to “add back” the various uncertainties abstracted away, even if they could be measured.

Analogs of the type envisioned are particularly useful in managing uncertainty because they can be used to simulate possible and plausible mechanisms when center-left on the three lower Fig. 1 scales. An analog’s mechanism is a consequence of interacting components following execution. Monte Carlo variations in component specifications, rules specifying interactions, and parameterizations can result in the phenomena generated during each execution being unique, which simulate the non-deterministic nature of biological phenomena. That variety can also represent uncertainty about generative mechanisms, experimental variability, and intra- and interindividual variability. The challenge then becomes to follow a disciplined protocol, as done in Sheikh-Bahaei and Hunt⁷², Hunt et al.¹¹⁰, and Lam and Hunt¹¹⁴, to identify and apply constraints in conjunction with in silico experimentation (see Definitions Sidebar) to systematically shrink the space of acceptable Monte Carlo variations. Having multiple analogs of the same referent is an acknowledgment and representation of uncertainties that can shrink but not vanish.

37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 **Avoiding information loss, “warts and all,” is essential**

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A product of modeling efforts cited in the reviews, irrespective of model type, is derived measures that are recorded for use by others. Examples include mean predicted ED₅₀ (\pm SD), clearance, half-life, volume of distribution, etc. Such derived measures are lossy (information is lost). Information present in the raw experimental observations is lost. Information loss is a concern: later, it may prove critical. Today, preventing such information loss can be challenging. So doing requires that proper measures were taken to preserve, manage, and transfer information. During a project’s lifetime (and thereafter), it requires attention to those preservation details across different functional groups through each development stage, from preclinical to post-marketing. The risk of critical information loss increases for conceptual model descriptions enriched with quantitative, mechanistic, pharmacological, physiological, and systems biology details that do not readily reduce to simple, mathematical or statistical descriptions. Reliance on derived measures portends to become a likely scenario in the emerging, model-based drug development paradigm.

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Examples described in Supplement—Uses^{74–103} illustrate that derived measures acquired during an early R&D stage can influence the perspective taken or focal aspect of interest at a later stage. Although the emphasis of this article is on AB M&S methods, we stress that these derived measures along with highly abstracted models are essential: researchers need them. They anticipate using them to provide a much

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needed bridge from particular and specific concrete modeling to the more powerful generalized models from which they will develop the theory for therapy controlled normal-to-morbid or diseased-to-normal transitions. For this reason, the framework must facilitate access to, and the analog-based knowledge repository and framework must house, curate, and facilitate access to both analogs and derived measures linked to their metadata.

Consider measures derived from multiple different models separated in time, combined and extended beyond their original model use cases, and how they may influence downstream conceptual models used for go/no-go decision-making. Conceptual models can be expected to push the go/no-go decision in one direction. A quite different direction may result if all the original models, including those that at an earlier time were judged “failures,” could be re-run together to directly inform decision makers. When productivity is on the line, such risk is not worth taking. An analog based knowledge repository fulfilling the requirements presented below will guard against such loss. Having intuitive, easily understood analogs will reduce dependency on, and usefulness of, lossy, derived measures to inform domain experts’ conceptual models.

DECISION SUPPORT REQUIRES A UNIFIED FRAMEWORK

Today, domain experts rely primarily on their own conceptual models— informed, of course, by computational models—to make go/no-go decisions. Improved productivity can be achieved by changing that relationship: domain experts make go/no-go decisions after using simulations to explore many scenarios within a computational framework built and equipped specifically for scenario exploration in addition to enabling the multiple M&S methods needed to satisfy the requirements below. It will be the “framework” within which all model uses occur.

To enable satisfying the variety of Table 2 uses, we envision the framework and its content being an up-to-date instantiation of all accumulated, new, and proprietary mechanistic knowledge in an accessible, easily understood, observable, and interactive form. As a consequence, R&D project team members will have reduced dependency on the corresponding, difficult to challenge, conceptual mechanistic models of current and past domain experts. Achieving the framework will require assembling and organizing the project’s associated variety of data, of all types (in-house and literature-extracted) in ways that enable automated use by a variety of model types.

Current experiment records and/or protocols capture and preserve some current, underlying, mechanistic conceptualizations, however that contextual information is typically decoupled from data and can become unavailable in subsequent phases of development. A good practice will be that information is documented and provided as part of annotation within the framework. In order to effectively incorporate data, especially wet-lab data across discovery and development stages for future use, automated M&S capabilities will be needed that enable and facilitate metadata annotations, which may be hierarchical, multi-perspective and include biological, anatomical, and physiological details across biological scales. Such metadata will not be ancillary, as in OpenABM¹¹⁵, and will be used within the framework for automated composition and falsification, as well as by users for the curation and evolution of the components. Under Resources, we list currently available tools that can be used to organize and complete the preceding tasks.

The envisioned framework will become an **analog based knowledge repository**. It will provide methods for storage, curation, composition, and execution of analogs representing what is known about domain-

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specific referent systems. Its core constituents (specific items) will be data, semantic relationships, workflow actions, and computational components. There will also be a variety of derived constituents including data sets, semantic networks (e.g., XML ontologies), workflows, plus analogs and their components.

As an example of knowledge repository decision support use, consider a task to estimate the likelihood of success for a clinical trial given a compound and cohort sample specifications. The following may seem futuristic, yet tools for enabling all capabilities (listed under Resources) are in use today within different domains. The project's inter-disciplinary team, including regulator scientists, statisticians, programmers, regulatory staff, etc., populate the knowledge repository with experimental protocols (Workflows under Resources), experimental data sets, analog mechanisms (Executable models under Resources) representing the cohort and compounds, and maps between the terms (objects, methods, variable, parameters, graphs, etc.) used in all these elements. Software agents and actors within the repository simplify the process, where an actor will be the entity within the framework that *acts* of its own volition. A user then specifies a set of objectives or criteria for a successful (or unacceptable) outcome for the clinical trial and assembles at least one analog that might plausibly generate data satisfying the objectives. Repository agents facilitate the composition by periodically checking the consistency and completeness of the evolving analog. The user then executes the analog according to study design workflow(s).

Execution results will exhibit the systemic causation and variability generated by fine-grain, networked events embedded in analog components. Repository agents will compare and contrast the results to the objectives and present the user with similarity scores validating or falsifying analogs. Repository agents may also present a suite of alternatively composed analogs consistent with the data, ontologies, and workflows previously installed. The initial similarity scores provide a rudimentary estimate of the likelihood of success for the clinical trial. Further execution and similarity scores of alternative analogs provide refinement of and confidence (or the lack thereof) in those estimates. Once requirements have been satisfied using tools like those listed under Resources, we envision all of the preceding being completed within hours.

As a technical note, an analog may contain components based on different formalisms. Some may be graph theoretic. Some may use ODEs. Others will be (or will use) agents. The preceding discussions illustrates that referring to the modeling activity as being agent-based is misleading. Agent-directed or agent-oriented are more accurate descriptions¹¹⁶.

43 FROM PARTICULAR TO PARAMOUNT M&S USES

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45 We worked through each of the cited reviews and commentaries⁷⁴⁻¹⁰³ and identified more than ninety
46 general and specific envisioned M&S uses. Although each article presented its assessment from a
47 particular perspective, there was, as might be expected, considerable overlap in specific uses. That
48 overlap guided and facilitated clustering them into seven categories that span all pharmaceutical R&D
49 activities. Given uses, we sought general requirement statements that would subsume two or more uses
50 within each category. They are listed in the next section.
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Clustered Examples of Specific M&S Uses

These examples (selected randomly) were drawn from those listed in Supplement–Uses. They illustrate the diversity and scope of envisioned^{74–103} M&S uses.

Knowledge integration

Quantitatively address questions concerning the functional relationship between prognostic factors, dosage, and outcomes.^{87,94,97}

Integrate the basic components to describe and understand the complex interplay between the pharmacology of drug action and (patho-)physiological systems.^{86,94}

Management of uncertainty

Account for uncertainty in the underlying assumptions and thus resulting prediction of drug effects.^{77,92}

Decision support

Document decision making from discovery through to regulatory filing and improve answering post-filing questions and approval, as well as life cycle management of the asset.⁹⁷

Provide a decision-making tool for selecting effective and safe doses, optimizing study sample sizes, evaluating alternative trial designs and making rational go/no go decisions based on the probability of achieving predefined study goals.^{76,79,80,92,97,98}

Preclinical and clinical development

Facilitate design and/or selection of lead compounds, selection of the first-in-human dose, early clinical trial design, and proof-of-concept studies of experimental drugs and drug combinations.^{75,76,83,84,86,103}

Simulate outcomes of alternative study designs before the experimental investigation commences—incorporating different doses and/or different patients and computing the probability of a successful trial given the characterized patient population and proposed treatment regimens.^{76,79,87}

Predict the toxic potential of chemicals and human adverse effect, and generate hypotheses about the putative molecular mechanisms of chemical-induced injury.^{95,100}

Drug-disease modeling

Use to understand the relationship between drug effect and the natural progression of the underlying disease.^{77,86,92,94}

Describe macrophysiological processes within a particular disease state and use to understand likely modulation of those processes with specific interventions.⁷⁴

Drug-drug interaction, special populations

Guide investigations in pediatric, the elderly and other special populations.^{77,85,89–92,96} Identify and assess complex DDIs early in drug development so that clinical studies could be planned or prioritized to assess the risk.⁸⁰

Prediction

Allow for extrapolation of the PK properties across species and compounds^{86,87,90,96}

Ultimately predict human PK from in silico, in vitro, and physicochemical data.⁸⁴

Paramount uses

The following Paramount M&S uses subsume the particular uses in Supplement–Uses.

Knowledge integration

Given multiple organizational perspectives (disease state, prognostic factors, drug characteristics, cohort variability, disease progression, drug effects, timelines, budgets, etc.) and multiple data sets (qualitative and quantitative; some possibly incommensurate) from various experiments and experimental models, solve for a collection of alternative, composable, explanatory mechanisms parameterized by, and validated against, available data. Here, “solve” is defined as applying constraints within an iterative protocol (see Tang and Hunt¹¹⁷, Park et

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al.¹¹⁸, Engelberg et al.¹¹⁹ for examples) to shrink a set of possible mechanisms into a much smaller set of plausible (supported early by qualitative validations) and incrementally more likely mechanisms (supported by quantitative validation).

Use collected mechanisms to assemble concrete, consistent, comprehensive, clinically relevant stories about the co-evolution, during and following treatment, of subject (multiscale), the condition being treated, and treatment as well as ADME plus response monitoring in the case of a drug. In this context, a story is the narrative created during simulation, and a simulation results from executing an in silico experiment. There are several reasons why a good simulation story is important¹²⁰. Use assembled stories to discover and make explicit potential conflicts, voids, and ambiguities within an analog based knowledge repository, thereby providing immediate predictive and analytical use, while bringing into focus paths for repository improvement.

17 *Management of uncertainty*

18
19 Present for in silico experimentation, plausible mechanisms exhibiting variability, both composite and singular,
20 that are qualitatively and quantitatively similar to that seen (or expected) in laboratory experiments or clinical
21 trials, including matching changes in variability across different cohorts and study designs. Use simulations to
22 estimate probability of achieving clinical target efficacy outcomes, and when feasible, estimate probability of
23 specified, undesired effects.

24 *Decision support*

25
26 Present contextualized assemblies of plausible mechanisms parameterized to provide an evidence-based
27 justification for componentized estimates of likelihood of success at critical stages within the development
28 process. Use the assemblies and their stories to estimate efficacy and safety windows, including confidence
29 intervals, and to demonstrate sample sizes within appropriate population cohorts needed for constraining study
30 outcomes to within those windows.

31 *Preclinical and clinical development*

32
33 Preclinical and clinical development along with post-marketing uses are covered by requirements listed above
34 and below.

35 *Drug-Disease Modeling*

36
37 Solve for plausible mechanism composites satisfying multiple long-term aspects of diseases, drug effects and
38 fates within cohorts, placebo effect, and disease modifying interventions. Use those mechanisms to predict
39 compound behavior (PK) within contexts of interest, including hypothetical mechanisms for lack of adherence,
40 dropout, and multiple drug interaction.

41 *Drug-drug interaction, special populations*

42
43 Solve for plausible mechanism composites of compound interactions of interest, including time-dependent
44 inhibition, induction, and competition between a parent compound and its metabolites. Solve for plausible
45 mechanism composites for various cohorts (animals, children, adults) based on classifications of compound
46 behavior in each cohort. Hypothesize and build mechanism translation maps between analog cohorts (e.g.,
47 between adults and children). Use plausible translation maps to design clinical trials for human cohorts.

48 *Prediction*

49
50 Solve for plausible mechanism composites by multi-objective search within constraints defined by fine-grained
51 classifications of cohorts (particular attributes at multiple levels and scales) and compounds (e.g., particular
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10 physicochemical properties), including their formulation, across model types (in vitro to in vivo, animal to
11 human). Use the plausible solutions to predict the outcomes of precise and particular regimens on individually
12 characterized cohorts, both across (translation) and within model types.

13 REQUIREMENTS

14 To enable all Paramount uses, the framework must enable, and analog systems must meet, these five
15 requirements.

- 16 1. An analog's components and spaces will be concrete (enabling knowledge embodiment), wherein its details
17 will be directly defined by its use cases. Analog components will be somewhat modular, in schedule as well
18 as state. So doing helps accomplish the following framework activities.
- 19 a. It enables defining and annotating component- and module-to-biological counterpart mappings,
20 making them explicit, intuitive, and easily understood. It enables experimentation on concrete
21 analogs. It is essential for wet-lab R&D scientists and decision makers to easily follow, interpret,
22 and comment, unassisted, on simulation details. For that, the embodied knowledge needs to be easily
23 accessible, which requires transparency in representation and execution—form and function.
- 24 b. It enables making modules quasi-autonomous and thus more biomimetic^{66,105}. Analog components
25 composing virtual cells, organs, animal models, and ultimately individuals, must exhibit some level of
26 autonomous behavior in order to improve similarity with biological counterpart phenotypes, while
27 increasing their explicative and predictive utility.
- 28 c. Components can be adapted easily to represent different past and future experiment designs and
29 protocols.
- 30 d. It is straightforward to change mechanistic detail (granularity, resolution) to simulate additional
31 attributes or experiments. It facilitates scaling (translation, morphing) among in silico experimental
32 systems to represent transitions from in vitro to animal models, from animal model to human cohorts,
33 and from normal health to morbid.
- 34 e. It enables reusing analogs and components along with their embedded knowledge, for study of new
35 chemical entities (or biologics) and new intervention scenarios under similar or different morbidity
36 constraints or epigenetic influences.
- 37 f. It facilitates verification through unit testing, where each component can be tested in isolation as well as
38 in the composed analog context.
- 39 g. It facilitates versioning, where each component can evolve independent of other components.
- 40 h. It enables building trust in surviving analogs by accumulating direct in silico-to-wet-lab validation
41 evidence, where measures taken during in silico experiments are mapped quantitatively to counterpart
42 measures taken during wet-lab experiments. So doing reduces reliance on derived measures, which can
43 mask information loss, assumptions, and uncertainty removal. Many of those validation exercises will
44 rely extensively on pharmacometrics and conventional modeling methods.
- 45 i. It facilitates archiving analog and mechanism evolution along with in silico experiment successes and
46 failures within the framework. The latter is particularly important. When an analog or in silico
47 experiment fails in some way, we acquire new knowledge, e.g., a feature of an analog mechanism
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thought to have a particular in vitro biological counterpart, does not. However, in a different context, that mechanism or some variant may prove useful.

- 6 2. Components and spaces can be assembled easily to simulate current, past, and future laboratory or clinical
7 experiments. Generating many alternative, plausible, testable (through *in silico* experimentation),
8 components for each function/structure and then selecting against those that fail, is needed to insure
9 generation of new knowledge. So doing helps accomplish two framework activities.
10
11 a. It becomes increasingly easy to construct (plug together) and explore alternative mechanistic
12 hypotheses and intervention scenarios. It facilitates contrasting their predictions during simulation.
13 So doing can help avoid dictating “best methods” prematurely. The latter keeps the door open for
14 yet-to-be-stated M&S uses while increasing opportunities for serendipitous insight and/or
15 discovery.
16
17 b. It becomes increasingly easy to construct multiscale, multiresolution, multi-attribute analogs
18 (eventually individualized virtual patients) composed of heterogeneous (form, function, methods,
19 formalisms, etc.) components.
20
21 3. Simulation experiments are feasible in the presence and absence of *ce*-objects. They are also feasible in the
22 presence of multiple *ce*-objects. Components within analogs can recognize different *ce*-objects and adjust
23 their response accordingly.
24
25 4. Coarse grain (from the perspective of biological organization) phenomena will derive mostly from
26 local component interactions at a finer grain (local includes a living entity’s immediate environment).
27 When required, finer grain mechanisms can respond to coarser grain phenomena.
28
29 5. Semi-automated modeling methods are needed to more rapidly complete three critical activities:
30
31 a. Conduct *in silico* experimentation to explore and shrink spaces of competing mechanistic
32 hypotheses plus alternative mechanism instantiations and parameterizations.
33
34 b. Use cross-model validation methods (based on quantitative similarity measures) to discover
35 parsimonious options to increase and decrease component and analog granularity when
36 milestones change and when new questions require new use cases, which necessitates changing
37 targeted attributes and/or shifting attention to new aspects and phenomena.
38
39 c. Discover testable hypotheses about how changes in clinical, field, or laboratory measures may be
40 linked mechanistically to observed or observable changes in particular biological level
41 phenomena, especially molecular-level phenomena.
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44 MECHANISM-BASED APPROACH 45

46 New projects are typically initiated based on evidence (even if limited) supporting conceptual mechanistic
47 models (morbidity or disease progression, cause-effect, pharmacology, clinical outcomes, etc.) that often
48 include hypothesized molecular targets offered by domain experts. There are large gaps in the
49 mechanistic knowledge landscape that must be filled strategically to facilitate making “correct” go/no-go
50 decisions. The mechanistic landscape spans cell cultures, model organisms, and humans. It also spans
51 pharmacology, toxicology, disposition, metabolism, and more. Today, no one member of the R&D
52 enterprise has a comprehensive “view” of that landscape, yet it is clear from the cited experts that full
53 knowledge of the current state of that landscape and what can be predicted from it is needed at each
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7 go/no-go decision juncture. Knowledge of—or use of one or more features on—that mechanism
8 landscape is common to all identified model uses.
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11 The ability to navigate, use, and leverage current mechanistic insight is a common feature of all
12 Paramount uses. Enabling those uses requires transitioning from models that are separate and distinct
13 computational (or diagrammatic) descriptions of conceptual representations (e.g., the systems biology,
14 PBPK, and pharmacodynamic models discussed in the cited reviews) to concrete instances of that
15 knowledge. Doing so is feasible using synthetic analogs of mechanisms⁶⁶. We create analogs by
16 combining (plugging together) specific elements, often varied and diverse, so as to form a coherent
17 biomimetic whole. The analog is synthetic because it is a software mechanism constructed from extant,
18 autonomous components (in this case, executable software components) whose existence and purpose are
19 independent of the model or mechanistic landscape that they comprise. The expectation is that, upon
20 execution, the interacting elements and components—the mechanism undergoing simulation—will
21 exhibit event sequences and outcomes that are measurably similar to counterpart mechanisms within the
22 corresponding wet-lab experiments that will be used to validate the analog. See Yan et al.¹²⁰, Lam and
23 Hunt¹¹⁴, Tang and Hunt¹¹⁷, Engelberg et al.¹¹⁹, and Park et al.¹¹⁹, for validated examples synthetic
24 analogs and their mechanisms, all designed for use center-left on the three lower Fig. 1 scales.

25 Exploratory iteration

26 One final, critical capability is needed in order to enable the remaining Paramount uses. It must be
27 straightforward to repeat any simulation experiment using a different compound, set of compounds, or no
28 compound. So doing can be accomplished most easily by building analogs using object-oriented software
29 methods and using different mobile objects to map to different compounds of interest. We require that
30 objects representing drugs can be added (or not) and, when “inactive,” their presence will not interfere
31 with any already validated mechanism. Examples of that approach are provided in Sheikh-Bahaei and
32 Hunt⁷², Lam and Hunt¹¹⁴, Park et al.¹¹⁹, Yan et al.¹²¹, and Sheikh-Bahaei et al.¹²². In those reports,
33 one compound object maps to a very small amount of referent compound in a small aliquot of measurable
34 material taken from a referent wet-lab experiments, such as culture media, blood, tissue, etc. Objects that
35 map to particular chemical entities of interest or their metabolites (hereafter, *ce*-objects) will carry
36 information that distinguishes one from another, such as structure specifications and particular
37 physicochemical properties. It follows that any analog component that might feasibly interact with a *ce*-
38 object must be able to “read” structure specifications and particular physicochemical properties, and use
39 that information to adjust (or not) its interactions with that object.

40 To enable the latter, analog components will need to be “intelligent” (able to use artificial intelligence
41 methods): they will be programmed with the results of many earlier validation and falsification
42 experiments and can—absent user intervention—arrive at a customized parameterization that determines
43 how they will interact with a new *ce*-object. To illustrate, imagine that analogs of each of a battery of in
44 vitro model systems have achieved degrees of validation for ten compounds. One analog’s referent is an
45 in vitro system used to characterize metabolic profiles and predict human metabolic clearance. Focus on
46 that analog: upon validation, for each mechanistic event, it retains its parameterizations for all ten *ce*-
47 objects. The project team needs an answer to this question. Given three, competing, new chemical
48 entities, are their expected metabolic clearance values within a target range? Each analog component, for
49 each unique mechanistic event, can use available framework tools, follow a provided protocol, and
50 construct a predictive map from the space of selected structure specifications and particular
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physicochemical properties to the space of validated parameterizations. We extend the mapping to the three new compounds and arrive at unique analog parameterizations for each *ce*-object counterpart. We then conduct analog clearance experiments using each of the three *ce*-objects. We use the results to predict wet-lab clearance measures. Sheikh-Bahaei and Hunt⁷² described a prototype example of such a protocol. With a knowledge base of only ten compounds, we would have only limited trust in those predictions. However, we would expect to have more trust after doing the same using a knowledge base of fifty compounds. At that stage we could begin characterizing families of compounds as well as particular molecules. As more information is embedded, the knowledge repository increasingly facilitates the work of the domain expert.

The same basic approach can be used to explore expected outcomes of in silico toxicology experiments, experiments in analogs of animal disease models, and even analogs of normal and special human cohorts. There would be no technical barriers to simulation experiments that explore possible drug-drug interactions.

21 Beyond Paramount uses

22 Figure 1 helps bring into focus important challenges faced by any new, high risk, high gain
23 pharmaceutical R&D project. It can be characterized as being left of center on the bottom three scales. A
24 task is to acquire just enough new information and knowledge (move right in Fig. 1) to make better-
25 informed, “good” go/no-go decisions sooner within budget constraints and in the face of considerable
26 uncertainty. The expectation is that simulations will use available knowledge to provide essential
27 information and/or guidance moving forward. To do so, M&S methods must be engaged at the start of
28 the project. Otherwise there will be considerable risk that M&S efforts will lag behind wet-lab efforts.
29 The logical beginning scenario would be to pull together components from models successfully
30 supporting more mature projects, modify them as appropriate, and assemble them to begin being
31 synergistic with wet-lab experiments. That scenario is an example of model uses beyond those that
32 directly support product development and approval. It also speaks to requirements, covered by those
33 above, which have apparently not yet been considered.

34 A related, also essential use will occur once a new product has been approved: revisit the process in silico
35 (from start to finish) to explore alternative R&D, knowledge acquisition paths that would have been more
36 time, cost, and/or knowledge effective. To do so will require simulating phases of the R&D process,
37 including various wet-lab experiments performed or not. Such exploratory simulation may seem
38 futuristic, but it is easy to believe that, with such capabilities, the field will have achieved dramatic
39 productivity gains and that is the objective. These additional M&S uses illustrate that future development
40 of simulation models must take place within a common framework, if the simulations are expected to
41 make a lasting contribution to the knowledge base. Within the envisioned framework, previously used
42 models will still exist: they and their components will be concrete software devices that can be reused. Of
43 course, they will always be incomplete analogs of their real world counterparts. Simulated R&D
44 activities will be analogs of past or future, real or considered R&D activities. None of these analogs,
45 however, will be fully detailed or fully validated. Because we will be center-left on the bottom three Fig.
46 1 scales, we know that they will (always) be flawed in ways yet to be determined. Those flaws will be
47 hidden by built-in uncertainties. Note that there are unknown risks to abstracting away those
48 uncertainties, leaving behind only a model of a single mechanistic hypothesis.

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Simulations that support and add plausible detail to early conceptual models, such as hybrids of systems biology, PBPK, and pharmacodynamic models, will be useful. Simulation models that can also falsify aspects of those conceptual models, earlier rather than later, will be especially valuable because hypothesis falsification, not validation, generates the new knowledge that will be needed for making go/no-go decisions^{123,124}. Enabling mechanism falsification in addition to mechanism validation is another, important use not specifically identified in the cited reviews. Falsification of an analog requires that its mechanism be concrete and particular⁶⁶. Plausible conceptual mechanisms, especially those that are more complicated, can in theory be falsified using wet-lab experimentation, but doing so can be challenging and time- and resource-intensive.

Analog based knowledge repository and agent-based models

Representing within a knowledge repository the variety of data structures, experimental observations, and documented biological phenomena that may influence go/no-go decisions during the R&D projects is beyond the scope of any one model of computation (MoC). A successful analog based knowledge repository will require the co-existence of multiple, occasionally inconsistent, yet equally valid, models of the same referent(s), as has been done within other domains¹²⁵. Inconsistency robustness¹²⁶ is important to the aspect-oriented nature of scientific modeling and simulation^{66,105,127}. The management of inconsistent models is part of the strategy for integrating MoCs into a coherent knowledge repository. The choice of underlying MoC for any particular activity is driven by the focal aspects or model (analog or component) use cases. Variety in aspects is better realized by variety in MoCs. For example, a dataflow MoC can co-exist with a discrete event analog of a mouse cancer model, the former representing a functional relationship between high volume population-oriented variables (like concentration in a PBPK model) and the latter representing mechanistic relationships between unique, biomimetic components. For the foreseeable future, such a repository will not, itself, be agent-based, but it will be partially agent-directed¹¹⁵. Agents such as Experiment Agents used in our work^{119,128-130} follow protocols and perform tasks exactly analogous to those human modelers perform: set up and execute various models (analogs, modules, etc.) and use pharmacometric methods. Drawing on work from Lee and colleagues^{125,131,132}, we anticipate no restrictions being placed on MoCs, except where required for managed composition, execution, and analysis as has been done with Ptolemy II¹²⁵ for M&S distributed scenarios. Depending on use-case requirements, analogs may be realized by any given MoC, including continuous-time systems, ABMs, ODEs, systems and process networks, Stream X-Machines, etc.

Conclusion

An eruption of recent articles, including those cited⁷⁴⁻¹⁰³, is focusing attention on the declining productivity crisis stressing pharmaceutical R&D. The hundred plus authors of the more than thirty cited reviews and commentaries argue from different perspectives (pharmacometrics, quantitative and systems pharmacology, model-based drug development, etc.) for expanded use of M&S methods as the primary means to reverse the downward productivity trend. They describe more than ninety particular M&S uses. The Example M&S sidebar includes particular examples. They were merged into Paramount uses listed above. We made the case that facile realization of those uses will require use of an analog based knowledge repository that fulfills five requirements. AB M&S methods will play important roles along with those methods already in use, but additional capabilities and methods are required. Importantly,

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6 there are no technology gaps. The five requirements can be satisfied by the tools listed under Resources,
7 which are in use within other domains.
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10 Reversing the productivity decline requires rethinking how M&S methods can and should be used within
11 the larger R&D process. It requires shifting focus from analysis of data to discovery of explanatory
12 mechanisms. The latter, conditioned Paramount uses, requires implementing the requirements listed
13 above. As illustrated in Fig. 1, and as explained in Hunt et al.¹⁰⁵ and Supplemental Text, so doing
14 requires increased reliance on relational grounding and diminished reliance on absolute grounding. It also
15 requires being clear about how computational models are being used and continuously exploring how
16 barriers to participation in M&S activities can be lowered.
17

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48 **Figure captions**
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50 **Figure 1.** A particular analog use case can be characterized by an approximate location on each of the four lower
51 scales. Scale location along with specifics about how and for what the simulation model will be used within the
52 larger R&D context, determine which M&S methods are most appropriate for a given use case. Within a
53 pharmaceutical R&D context, a use case includes details of the specific, biology-focused wet-lab experiment that
54 analog execution is intended to model in some way. Depending on use-case location on the scales, an analog can be
55 located anywhere along a spectrum of software devices (models) ranging from synthetic (all components designed to
56 be plugged together and are thus replaceable) to purely inductive models. *System Information* includes current
57 conceptual knowledge about the mechanisms on which the wet-lab experiment focused. As the R&D process
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advances, evidence will shrink the space of possible mechanisms. The result will be a set of plausible analog mechanisms supported by validation evidence. Later, that set too will shrink. The result will be a smaller set of likely mechanisms (those that have survived several falsification experiments). The R&D project's product can be successful without being able to designate key mechanisms as either actual or likely. Actual mechanisms are typically known for engineered systems, but are typically lacking in therapeutics. Grounding is discussed in the Grounding Sidebar; additional information is provided as Supplemental Text. Conditions on the far right of the bottom four scales are supportive of models (typically, continuous equations) that rely exclusively on absolute grounding. Hunt et al.¹⁰⁵ make the case that when left of center on one or more of the bottom three scales, models should rely more on relational grounding.

14 Resources

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Listed below are available, open-source tools of the type that can be used now to begin satisfying the listed interactive Knowledge Repository requirements.

19 Databases

20 PostgreSQL (relational) - <http://www.postgresql.org/>
21 ZOBD - <http://zodb.org/>
22 NoSQL - <http://nosql-database.org/>
23 RDF/SPARQL - <http://www.w3.org/TR/rdf-sparql-query/>

24 Data [de]composition

25 R - <http://www.r-project.org/>
26 HDF - <http://www.hdfgroup.org/HDF5/>

27 Semantics:

28 Protoge - <http://protege.stanford.edu/>
29 Ontopia - <http://www.ontopia.net/>
30 Jena - <https://jena.apache.org/>
31 Pellet - <http://clarkparsia.com/pellet/> (complete)
32 Racer - <http://www.sts.tu-harburg.de/~r.f.moeller/racer/> (complete)
33 Hermit - <http://hermit-reasoner.com/>

34 Executable models

35 Code

36 Eclipse - <http://eclipse.org/>
37 Netbeans - <http://netbeans.org/>

38 Graphical programming

39 Ptolemy II - <http://ptolemy.eecs.berkeley.edu/ptolemyII/index.htm>
40 NetLogo - <http://ccl.northwestern.edu/netlogo/>
41 ArgoUML - <http://argouml.tigris.org/>

42 Modeling infrastructure

43 JAMES II - <http://wwwmosi.informatik.uni-rostock.de/mosi/projects/cosa/james-ii>
44 CC3D - <http://www.compuCell3d.org/>
45 MASON - <http://cs.gmu.edu/~eclab/projects/mason/>

46 Actor model¹³³

47 Erlang - <http://www.erlang.org/>
48 Scala - <http://www.scala-lang.org/node/242>

49 Workflow

50 Kepler - <http://kepler-project.org/>

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Taverna - <http://www.taverna.org.uk/>
Galaxy - <http://galaxyproject.org/>
Triana - <http://www.trianacode.org/>

7 **Graphs**
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NetworkX - <http://networkx.lanl.gov/>
JUNG - <http://jung.sourceforge.net/>

11 **Related Articles**
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- 13 An G, Mi Q, Dutta-Moscato J, Vodovotz Y. Agent-based models in translational systems biology. Wiley
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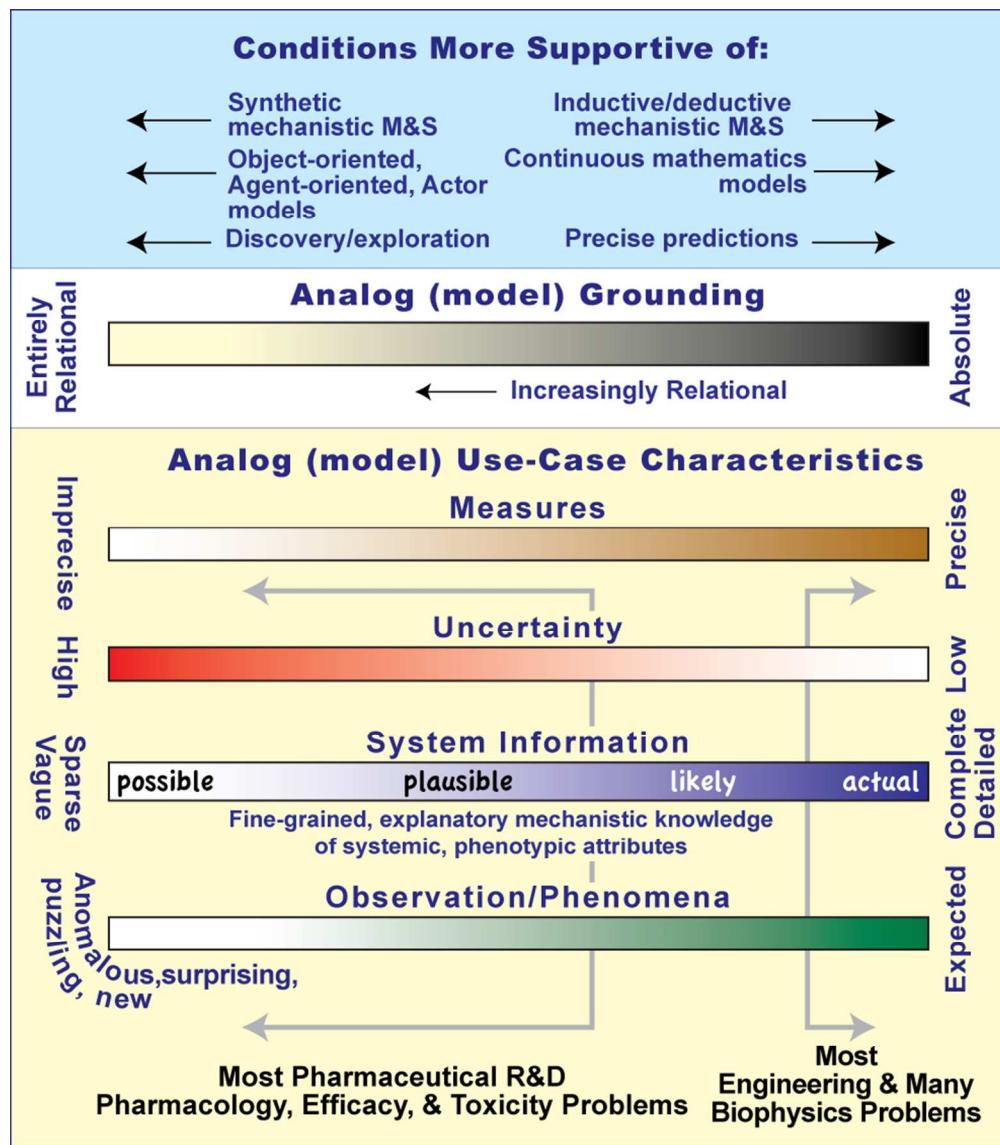


Figure 1. A particular analog use case can be characterized by an approximate location on each of the four lower scales.

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Supplement—Uses

Agent-Based Modeling: A Systematic Assessment of Uses and Requirements for Enhancing Productivity in Pharmaceutical Research and Development

Hunt CA, Kennedy RC, Kim SHK, Ropella GEP

Listed below are specific, current, desired, and envisioned modeling and simulation uses spanning the pharmaceutical R&D enterprise. The articles referenced are representative of many recent articles that discuss M&S in the context of strategies for reversing the productivity decline.

Knowledge Integration

- Integrate knowledge from all aspects of drug development (*in vitro*, *in vivo*, preclinical, clinical and post-marketing), thereby serving as a key decision-making tool, enabling rational, scientifically based choices at critical decision points. [8,9,10,11,12,13,16,18,19,21,22,23,24,28]
- Quantitatively address questions concerning the functional relationship between prognostic factors, dosage, and outcomes. [14,21,24]
 - Integrate/capture causal relationships between disease state, prognostic factors, drug characteristics, individual variability, and drug- and disease-induced changes in biomarkers and clinical end points obtained from all phases of preclinical and clinical development. [1,9,21,12]
 - Integrate sources of variability in exposure-response relationships, which in turn should enable the prospective prediction of the probability of clinical outcomes for specific genotypes and phenotypes and thus eliminate the practice of unguided clinical decisions for pharmacotherapy. [9,20]
- Integrate the basic components to describe and understand the complex interplay between the pharmacology of drug action and the (patho-)physiological systems. [13,21]
 - Allow the integration of the physiological structure, biochemical mechanisms and drug-related properties (e.g., membrane permeability, plasma and tissue protein binding, blood-to-plasma ratio, etc.). [3]
 - Integrate information derived from *in vitro* systems regarding interaction of a drug with enzymes and/or transporters. [16]
- Effectively leverage existing knowledge and guide future research and experiments in order to optimize drug safety and clinical outcomes. [1,2,4,10,11,12,19]
 - Summarize the knowledge in a ready to apply format. [5]
 - Quantitatively summarize all relevant data at the end of a compound's full development. [14]
 - Enable artificial intelligence applications to make inferences that would be difficult or impossible to achieve for human scientists. [30]
- Provide computer-based conceptualizations of the mechanism of disease and of the links between drug treatment and observed effects. [6]
 - Provide a comprehensive picture of drug action—both therapeutic and adverse—on cell-, tissue-, and organ-level physiological functions. [9,22]
- Integrate knowledge about growth, development, and maturation of various organs and tissues involved in drug metabolism and elimination across pediatric age groups to predict drug pharmacokinetics in children. [12,11,18]

- Act as a knowledge repository, continuing to be refined and incorporating new data as the candidate molecule progresses into clinical development. [1,2]
 - Provide a framework for integration of data related to drug interaction potential, and their capability to consider the time-varying concentrations of interacting drugs and account for physiological and pharmacokinetic complexities. [2]
 - Incorporate experimental animal data, as well as in-silico-derived and in vitro data, into a coherent framework, from which meaningful and reliable assessments can be made. [8]
 - Provide resources for open-software and open-data, collection and sharing, to facilitate communication and allow for growth of data-driven models [3,24,27,29]
- Integrate knowledge across multiple scales to facilitate the development of drug candidates [9,15,22,23,28]

Management of Uncertainty

- Explore both variability and uncertainty in experiments and clinical trial designs. [1]
 - Account for uncertainty in the underlying assumptions and thus the resulting prediction of drug effects. [4,19]
 - Formalize assumptions, and close gaps in data and knowledge. [24]
- Project the uncertainty and the probability of success in development programs. [21]
 - Illustrate and define the uncertainty in demonstrating efficacy and safety with different development programs as assessed by, for example, the probability of achieving the target clinical efficacy outcomes with various study design. [19]
 - Perform a team-based knowledge-gap analysis, which can provide a forecast of the impact of knowledge gaps on the outcome of future clinical trials, thereby providing management with a method to prioritize the laboratory investigations at the beginning of the development program. [6]

Decision Support

- Fulfill traditional roles to support labeling and confirm decision. [20]
 - Document decision making from discovery through to regulatory filing and improve answering postfiling questions and approval, as well as life cycle management of the asset. [24]
 - Support regulatory decision-making on chemical safety and risk of toxicity. [27]
- Provide a decision-making tool for selecting effective and safe doses, optimizing study sample sizes, evaluating alternative trial designs and making rational go/no go decisions based on the probability of achieving predefined study goals. [3,6,7,19,24,25]
 - Learn and confirm the key characteristics embedded within a drug candidate's molecular structure, with the goal of providing explicit, reproducible, and predictive evidence for optimizing drug development plan and resource allocation, enabling critical decision making, and eventually bringing safe and effective medicines to patients. [20,21,30]
- Support decision making on such issues as candidate selection, first-in-human dose finding, assessment of drug-drug interaction potential, and definition of appropriate study designs involving drug-drug interactions or inclusion/exclusion criteria for conducting studies of drugs metabolized by polymorphic enzymes. [7,16]
- Conduct decision analyses of the comparative benefits and risks associated with preventive and treatment strategies. [7,15,24]

Preclinical and Clinical Development

- Guide creation of an efficient clinical development strategy. [19]
 - More effectively define potential drug candidates and optimize clinical development by identifying appropriate patients, dose, and optimal clinical trial designs. [1,29]

- Facilitate design and/or selection of lead compounds, selection of the first-in-human dose, early clinical trial design, and proof-of-concept studies of experimental drugs and drug combinations. [2,3,10,11,13,29]
- Use to select the studies that would be most relevant to conduct or to replace the ‘guesswork’ that is common when prospective clinical studies are not feasible. [3,16]
- Help select compounds for clinical trials by integrating all the information for particular compounds into a mechanistic framework where selection can be made based on the expected human PK profile. [11]
- Evaluate/explore the performance of different designs based on the currently available information about the drug before a specific design is selected for the next study. [3,6,11,16,19]
 - Simulate outcomes of alternative study designs before the experimental investigation commences—incorporating different doses and/or different patients and computing the probability of a successful trial given the characterized patient population and proposed treatment regimens. [3,6,14]
 - Predict undesirable effects for safety assessment and support of lead selection and optimization. [27]
 - Help prioritize compounds prior to in vivo experimentation to reduce the number of in vivo animal studies performed in discovery, and ensure appropriate dose selection is made. [11]
 - Predict first-in-human dosage requirements in conjunction with traditional studies in laboratory animals to establish concentration-effect relationships regarding safety. [16]
 - Predict the toxic potential of chemicals and human adverse effect, and generate hypotheses about the putative molecular mechanisms of chemical-induced injury. [22,27]
 - Project drug PK profiles under various scenarios, and help determine whether there is a need for additional studies as part of risk-benefit assessment of new drugs. [11]
 - Evaluate the full time-course of systemic drug and metabolite exposure under all the conditions and situations likely to be encountered during clinical development and beyond. [17]
 - Relate drug exposure, in the compartment measured, to the pharmacological effect at the site of action. [24,26]
 - Use to understand the relationships between absorption and its associated parameters, and the interactions of drug substance properties and bioavailability, to guide the formulation development process. [10]
 - Perform clinical trial simulations to improve the design of future trials. [1,5,11,14,19]
 - Predict long-term safety early in drug development. [5]
- Translate in vitro findings into in vivo efficacy and allow streamlining of dose finding for Phase I and II studies as well as the assessment of new dosing regimens for their likely clinical efficacy and safety. [19]
- Characterize the relationships between the biomarkers and the preclinical/clinical outcomes, placebo effects, a drug’s pharmacologic effects both on and off-target-wise, and trial execution characteristics for both the desired and undesired response. [5,23,25]
 - Guide the identification and development of biomarkers that can serve to predict efficacy and safety during the late stages of preclinical development or the early stages of clinical development. [24]
- Predict the treatment effect as a function of dose, regimen and study design. [19]
 - Evaluate the impact of protocol deviations from a specific design, including the dropout and compliance behavior. [19]
 - Provide guidance for designing better randomized efficacy trials, by determining the appropriate experimental design (dose selection, treatment duration, population selection, etc.) that should maximize separation between side effects and efficacy while still maintaining a clinically meaningful benefit. [14]
 - Assess population variability of absorption after administration of drugs via other routes of extravascular administration (e.g., dermal). [16]
- Predict human testing results by integration of information of physiology and physicochemical properties of an investigational drug. [18]

- Predict drug clearance, tissue distribution and rate and extend of absorption, and plasma and tissue concentration time profiles. [11,18]
- Predict exposure/response to a drug and/or toxics not just in the plasma or blood, but also in remote and/or inaccessible compartments such as the brain and tumor tissues. [12,24]
- Provide the starting point for ‘stratified’ and/or personalized medicine. [11,16]
 - Enable binning of individual patient’s drug response into tranches to develop a limited set of appropriate treatment regimens (precision/individualized medicine). [9]

Drug-Disease Modeling

- Use to understand the relationship between drug effect and the natural progression of the underlying disease. [4,13,19,21]
 - Explore clinical trial designs and methods of data analysis to differentiate symptomatic versus disease modifying effects. [19]
 - Perform longitudinal analysis of disease progression, with all its components, such as placebo effect, lack of adherence and dropout. [14]
 - Simulate the impact of specific diseases (in individuals, clinical trials, and entire populations), and predict pharmacokinetics in specific disease states defined by etiology and severity. [11,12,17,18]
- Describe macrophysiological processes within a particular disease state and use to understand likely modulation of those processes with specific interventions. [1]
- Incorporate dual or multiple drug effects on disease complementary domains. [14]

Drug-Drug Interaction, Special Populations

- Guide investigations in pediatric, the elderly and other special populations. [4,12,16,17,18,19,23]
 - Anticipate pharmacokinetic differences in pediatric patients relative to adult patients and assist in the selection and optimal design of in vivo investigations. [17]
 - Explore “what if” scenarios to determine the most likely cause of altered pharmacokinetics in children. [12]
 - Help design and optimize conductance of clinical trials in special populations such as pediatrics, where optimal planning is needed to minimize the ethical and technical difficulties; for example, in pediatric clinical trials, by suggesting first dose/dose range or optimal sampling times, which is of great importance, as taking blood samples is more difficult than in adults and a main challenge in conducting pediatric clinical trials. [3,12]
 - Use for intra-human scaling from healthy adults to special subpopulations (diseased, the elderly, pediatrics, genetically unique subpopulations) to define differential organ dosimetry as it relates to efficacy and/or safety. [4,11]
- Dynamically evaluate the impact of a DDI with respect to the full concentration-time profiles of the interacting compounds. [17]
 - Assess more complex scenarios involving simultaneous dose-dependent inhibition and induction as well as competition for plasma binding, the inhibitory effects of both parent drug and metabolites. [17]
 - Analyze various elements of complex DDIs involving metabolites and nonlinearity with time. [16]
 - Forecast age-dependency and disease-dependency of pharmacokinetics, explore the variability expected in different patient populations, and provide guidance in the design of DDI studies. [2]
 - Capture the complex interplay between the parent compound and its metabolites involved in time-dependent inhibition (TDI). [2]
- Identify and assess complex DDIs early in drug development so that clinical studies could be planned or prioritized to assess the risk. [7]
 - Detect serendipitous connections between approved drugs and harmful or beneficial interactions when taken by the same patient. [30]

Prediction

- Allow for exploration of the PK properties across species and compounds [13,14,17,23]
 - Extrapolate knowledge from one drug class to another and more quickly address new therapeutic targets. [13]
 - Provide interpretation of inter-animal and inter-species PK differences (for instance, owing to different absorption or disposition), and extrapolation to humans. [14]
 - Identify, characterize, and explain the relationships between genetic and epigenetic changes and alterations in targets of interest within species-specific mechanistic contexts. [9]
 - Extend the above characterizations to patients to enable individualized &/or cohort tailored medicine. [9]
- Map formulation components and in vitro release profiles to in vivo PK. [10]
 - Use animal and potentially human ADME data to define the differential dosimetry that may ultimately aid in definition of tolerable daily intake allowances or risk profiles when linked to human exposure. [4]
 - Guide dosing and optimal sampling in first-in-human trials and in human health risk assessment to predict blood and organ concentrations that may be linked to safety end points. [4]
- Quantitatively evaluate temporal influences of covariate combinations (sources of the variability) (including genetics, BSA, age, ethnicity, gender, pregnancy, obesity, environmental factors, smoking, etc.) on mechanisms of interest, including ADME. [16,21,23]
- Predict outcomes of treatment protocols, not just in an “average” individual but in any cohort of interest that. [2,3,16]
 - Describe and/or predict drug PK and target exposure in cohorts characterized by different physiological, pathological, and/or morbidity attributes. [7,11,12,18]
- Ultimately predict human PK from in silico, in vitro and physicochemical data. [11]
 - Predict the drug PK, efficacy and side effects in a given individual with a known genotype make-up for relevant ADME and pharmacology proteins. [11]

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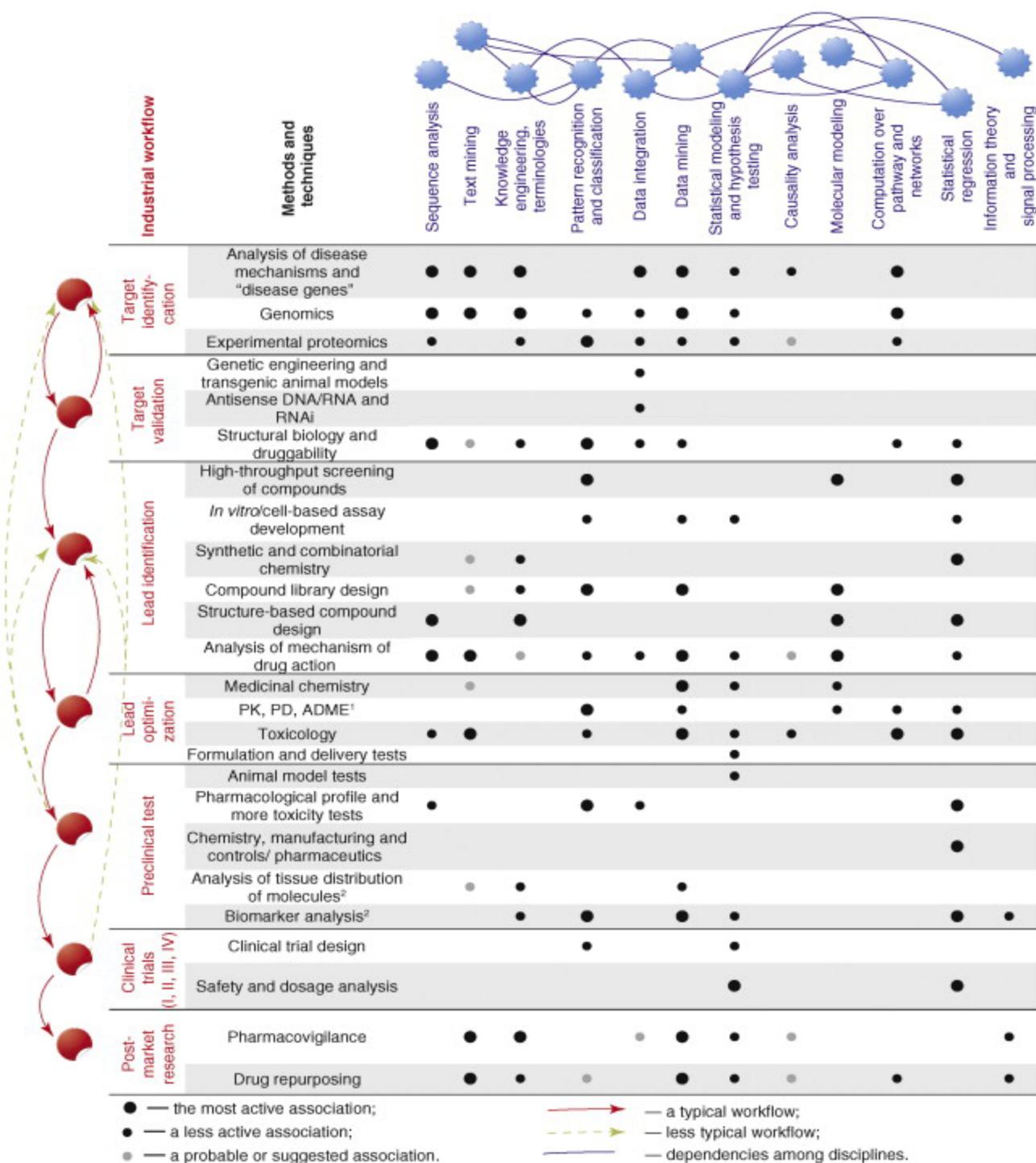
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Supplemental Figure S1
Agent-Based Modeling: A Systematic Assessment of Uses and Requirements for Enhancing Productivity in Pharmaceutical Research and Development

Hunt CA, Kennedy RC, Kim SHK, Ropella GEP



The figure above is reproduced with permission from [Yao L, Evans JA, Rzhetsky A. Novel opportunities for computational biology and sociology in drug discovery. *Trends in biotechnology* 2010, 28(4):161-70. doi: 10.1016/j.tibtech.2009.06.003]. The legend is adapted from the original.

This matrix diagram characterizes various roles of computational technologies within the drug discovery process, and indicates how they impact drug discovery. Traditional linear processes are shifting to become more parallel, simultaneous and cyclical. Red arrows indicate the traditional process and yellow dashed arrows suggest novel workflows that are being used increasingly to increase productivity.

Biomarkers and analysis of the tissue distribution of target molecules are the most recently introduced checkpoints; the FDA does not require them. Computational biology methods are listed along the top. Blue lines illustrate how methods are related.

The impact of each computational technique on each drug discovery stage is classified into three categories: actively or heavily used (large black dot), less actively used (small black dot) and our suggestion (small gray dot).

Chemical informatics is not emphasized because it relates to issues from chemistry and not biology. Chemical informatics comprises a wide range of approaches from computational and combinatorial chemistry that model lead properties and their interaction with targets. Examples include chemical structure and property prediction; structure–activity relationships; molecular similarity and diversity analysis; compound classification and selection; chemical data collection, analysis and management; virtual drug screening; and prediction of *in vivo* compound characteristics.

PK, pharmacokinetics; PD, pharmacodynamics; ADME, absorption, distribution, metabolism and excretion.



Supplemental Text

Agent-Based Modeling: A Systematic Assessment of Uses and Requirements for Enhancing Productivity in Pharmaceutical Research and Development

Hunt CA, Kennedy RC, Kim SHK, Ropella GEP

Adapted from Hunt CA, Ropella GEP, Lam TN, Gewitz AD. Relational grounding facilitates development of scientifically useful multiscale models. *Theoretical biology & medical modelling* 2011B, 8:35. <http://www.tbiomed.com/content/8/1/35/>

Essential roles of relational grounding in satisfying Requirements

The units, dimensions, and/or objects to which a variable or model constituent refers establish groundings. Absolute grounding: variables, parameters, and I/O are in real-world units. Each term is foundational and maps to a tacit entity having a conceptual or biological meaning. Relational grounding: variables, parameters, and I/O are in units defined by other system components. Variables and components may map to counterparts outside the system or have meanings that are unrelated to the real world. Biology uses relational grounding. Grounding issues do not pose problems for conventional models because they are most often focused narrowly on a single aspect of a system (e.g., a PBPK or gene network model). However, when the model is an analog that aims to describe multiple aspects (i.e., different phenotypic attributes), grounding problems emerge. To satisfy the above requirements, a spectrum of model classes, methods, and groundings will be needed: absolute grounding occupies one extreme; relational grounding occupies the other. The conventional model classes cited in the reviews, mostly pharmacometric and inductive, data-focused ODEs, which use absolute grounding, will remain important and will see critical uses, but how those methods are used within the framework will differ from those described in the reviews.

Inductive, data-focused, mechanistic, ODE models are accretions of at least three different model types: 1: conceptual models of biological mechanisms, features, and aspects; 2: equations that describe temporal phenomena of type 1; 3: measurement units that provide a quantitative 1:1 mapping from type 2 to measures of biological phenomena. The conceptual models are grounded to the biology via the literature, proprietary information, and expert opinion. Both types 1 and 2 may contain bias and/or questionable assumptions. Good science requires all three be made specific and concrete. Such model accretion reduces flexibility and makes reuse problematic. Progress in satisfying the Box 2 uses requires a different three-step approach. 1) Map specific biological features to actual, concrete, relationally grounded software objects and spaces that have execution protocols. They will become analogs. 2) Measure actual phenomena generated during executions. 3) Specify quantitative mapping models to relate measures of *in silico* phenomena to real (not derived: see below) measures of referent phenomena. Such model separation provides the required flexibility and encourages reuse.

Requiring relational grounding is essential because so doing enables synthesizing flexible, easily adapted, extensible, hierarchical analogs of the systems they mimic. Grounding to metric spaces and real world units—absolute grounding—provides simple, interpretive mappings between output, parameter values, and referent data. However, complex issues must be addressed each time one of the following occurs: expand the model to include additional phenomena; combining models to form a larger system; and/or model context changes. Expansions are challenging, even infeasible, when center-left in Fig. 1. A PBPK model, for example will have limited reusability when experimental conditions change or when an

assumption made in the original model formulation has been falsified. Reusability is hindered in part because the conflated semi-mechanistic ODE model and the model-to-referent mapping model have different uses. The components and processes in discrete event, object and agent oriented, biomimetic analogs need not have assigned units [1-6].

Grounding decisions impact managing mechanistic and related uncertainties within analogs. In ODE models grounded absolutely, variables and parameters are often expressed as precise mathematical values, even though their networked uncertainties are usually significant. Examples include the physiological parameters in mechanistic PBPK models. Representing uncertainty within such models is mathematically complex and can be problematic for large models. Integrating models from different contexts can require that the whole model be refitted, which should involve re-examination of the cumulative consequences of the networked assumptions. In contrast, probabilistic functions within analogs can represent inherent uncertainties conveniently.

An expectation running through the uses listed in Supplement—Uses is that models will evolve (become more complicated) as R&D advances and new mechanistic insight accumulates, which will require changing, adding, and removing component linkages within analogs. We have recommended [3] striving to keep component groundings relational. So doing facilitates component replacement, limiting any one component formulation solely to its coupling with the others. Any component can be replaced at will as long as the minimal I/O matching requirements are met. Starting with relationally grounded analog components allows the modeler to iterate progressively from qualitative to quantitative validation.

Validation will be based on similarity of phenomena generated during analog simulations to corresponding referent system phenomena. The similarity spectrum can range from qualitative to quantitative. With qualitative similarity, objects will either possess some quality, or they will not. Simulation and referent attributes are considered similar if they have (almost) the same qualities. With quantitative similarity, attributes are categorically the same but vary by magnitude and can be compared by some ordering relation (e.g., less than or greater than). It is always the case that a valid qualitative description is a prerequisite for (and provides constraints for) quantitative descriptions, in the sense that any quantities defined must relate to one or more qualities. Validation (or lack thereof) should act as an important determinant of what type of analog or model (and therefore, what type of grounding) to employ at different stages during project R&D.

Relational grounding facilitates scaling between wet-lab and animal models used during R&D (and between different cohorts of individuals). Consider scaling metabolic clearance of a particular compound in mice (ml/ min/g) to enable human prediction when clearance is grounded absolutely on concentration and time. Scaling to human clearance values requires applying mass, volume, and time scaling factors to all parameters simultaneously, knowing that each scaling factor is imprecise and uncertain. When scaled predictions deviate significantly from observed values (common), there is no way to ascertain which scaling factor(s) and/or which scaled parameter(s) is problematic. Within a relationally grounded analog, mass and volume scaling can be done separately and validated independently. Setting the scale for one variable in accordance with trusted validation data can help set the scale for other, related variables. Time scaling is more complicated [3]. It may require a separate scaling for each probability parameter. However, satisfying the requirements opens the door to using available methods and tools (Box 3) to automate analog-to-analog scaling for analogs grounded relationally.

Relational grounding will also facilitate development of theories of translation. One relationally grounded analog exhibiting the above requirements can be morphed into another. That morphing models conceptual translation and thus stands as a tentative theory of cause-effect translation. It can be directly challenged and falsified (or not). Importantly, gaining exploitable insight into normal-to-disease transitions can be best achieved with analog components that use relational grounding. Park et al. [4] provide an example. Such transitions will require change in how components at multiple levels are parameterized and/or interact. Alternative mechanistic scenarios will need to be explored and challenged.

Having components grounded absolutely makes such exploration problematic. Reliance on relational grounding simplifies mechanism exploration and makes the process more intuitive.

Satisfying the requirements requires that all analogs be articulated: consist of distinct parts, modules, and/or components, some of which are autonomous. However, articulation issues are orthogonal to grounding issues. A component that initiates and maintains its own run-time is autonomous. Mammalian cells can be autonomous in vitro. When analog components are quasi-autonomous, they can be effectively replaced by other components for which component I/O requirements are specified in ways consistent with biology. The extent to which a component is autonomous is handled by the clear specification and maintenance of component use cases (aspects, phenotypic attributes, experiment protocols, etc.) or, collectively, by the component's phenotype. A model will lack any autonomy as long as there is only one use case for given component and a single use case for all connected components. Autonomy can be established regardless of how a module is grounded, but only when targeted phenotypic attributes are clearly defined, which can be challenging when left-of-center in Fig. 1.

Relational grounding facilitates referent knowledge embodiment within analog mechanisms.

Computational biology markup languages standardize relationships between the terms. To fulfill the requirements, we must have explicit ontologies enabling specialization into technical programming (Box 3) and biomedical domain expertise. An expert must be able to examine an analog, its components, and simulation events without needing computational expertise. Achieving the knowledge repository will have parallels to the evolution of modern biomedical research. Biomedical scientists design and perform complex experiments without becoming experts in laboratory equipment, reagent design, and production. Progression from custom-built experimental to standardized lab products allowed scientists to effectively compress complicated methods. They were subsumed by engineering, production, and validation processes. That subsumption reduced experimental variability, facilitated experiment replication, and lowered costs, which freed scientists to build increasingly more sophisticated experiments atop complicated equipment (e.g., a cell sorter, a confocal microscope, monoclonal antibodies, transfection reagents, automated DNA sequencer). An analogous progression, progressed in time, must occur for the envisioned productivity gains to be achieved.

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