Bayesian AutoML for Databases via the InferenceQL Probabilistic Programming System

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Abstract InferenceQL is a probabilistic programming system for scalable Bayesian AutoML from database tables. InferenceQL is designed to help make Bayesian approaches to data analysis more accessible to broad audiences and to assist experts in auditing and improving the quality of data, models, and inferences. Unlike traditional probabilistic programming systems, InferenceQL provides automation for learning models using nonparametric Bayesian structure learning of probabilistic programs. Experts can override these models with custom probabilistic programs for specific subsets of variables and conditional distributions. For a broad class of models, InferenceQL can generate realistic synthetic data subject to constraints and can automatically compute exact probabilities and mutual information values. Finally, InferenceQL aims to enable scalable Bayesian model criticism via posterior predictive checks, data quality screening via conditional probability calculation, fairness auditing via conditional probability ratios, and synthetic data generation to enhance privacy. These capabilities are accomplished using constructs that interleave standard database queries with Bayesian inference.

Automated Bayesian inference from databases is important and useful in several ways. For example, many real-world databases have high rates of missing values, more fields than observed records, heterogeneous data types, high rates of data entry error, and other factors that complicate the application of traditional ML-based AutoML techniques [9, App. E]. Furthermore, many real-world applications benefit from uncertainty quantification, interactive model checking and model criticism, and conditional probability estimation for ad-hoc fairness auditing. These problems are naturally formulated in terms of Bayesian inference [11, 28].

InferenceQL is a probabilistic programming system for automated Bayesian inference from database tables. InferenceQL provides a domain-general mechanism for Bayesian structure learning [18] of probabilistic program source code [27], as well as domain-general mechanisms for scalable exact and approximate inference in these probabilistic programs. Users thus do not have to know how to write probabilistic programs in order to use InferenceQL to solve problems. Instead, users rely on automated data modeling techniques to navigate the design choices that might otherwise be handled by experienced modelers. InferenceQL also enables Bayesian inference operations to be interleaved with ordinary SQL operations, yielding complex database-native workflows for Bayesian AutoML. InferenceQL has been used successfully in field tests for a broad range of applications, including AutoML for clinical trial oversight in three real-world clinical trials.

This workshop paper introduces InferenceQL via an exploratory data analysis application. It also briefly reviews the system architecture of InferenceQL and the class of probabilistic programs that deliver its AutoML capabilities. It presents preliminary quantitative results from experiments comparing InferenceQL's modeling accuracy to GLM, VAE, and CTGAN baselines. Finally, it reviews related work, including both modeling formalisms and ML and database integrations, and discusses some limitations and broader impacts.

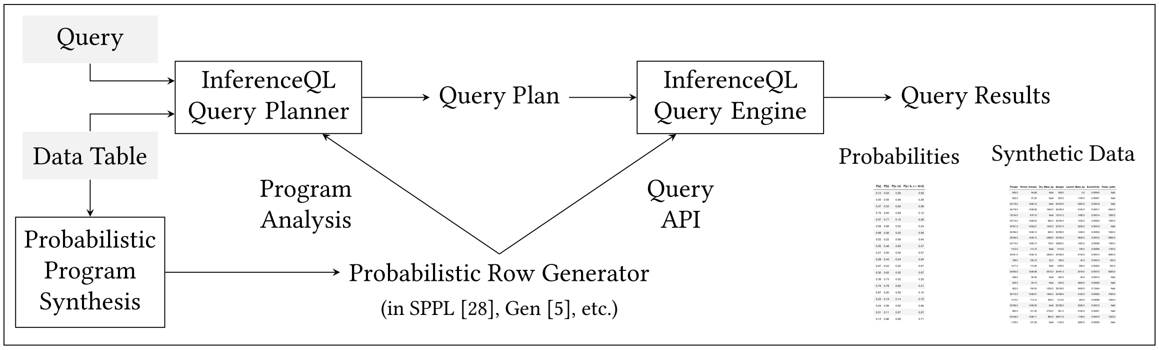


Figure 1: System architecture of InferenceQL.

Name	Country_of_Operator	Operator_Owner	Users	Purpose	Class_of_Orbit	Type_of_Orbit
Prometheus 1A	USA	Los Alamos Nati	Military	Technology Develo	LEO	Sun-Synchronous
Eutelsat 28A	Multinational	European Teleco	Commercial	Communications	GEO	NaN
SMDC-ONE 1.2	USA	U.S. Army Space	Military	Technology Develo	LEO	NaN
Lacrosse/Onyx	USA	National Reconn	Military	Surveillance	LEO	Intermediate
SMOS (Soil Mo	ESA	Centre National	Government	Earth Observation	LEO	Sun-Synchronous
Compass G-11	China (PR)	Chinese Defense	Military	Navigation/Global	GEO	NaN
Echostar 6	USA	Echostar Techno	Commercial	Communications	GEO	NaN
INMARSAT 4 F2	United Kingdom	INMARSAT, Ltd.	Commercial	Communications	GEO	NaN
Eutelsat 25C	Multinational	European Teleco	Commercial	Communications	GEO	NaN
Vinasat 2	Vietnam	Vietnamese Post	Government	Communications	GEO	NaN

Perigee_km	Apogee_km	Eccentricity	Period_minutes	Launch_Mass_kg	Dry_Mass_kg	Power_watts
500	506	0.00044	94.68	NaN	NaN	NaN
35788	35794	0.00007	1436.10	2950	1375	5900
483	789	0.02184	97.40	3	NaN	NaN
574	676	0.00729	97.21	14500	NaN	NaN
759	760	0.00007	100.00	658	630	1065
35776	35799	0.00027	1436.15	2300	NaN	NaN
35775	35798	0.00027	1436.12	3700	1493	11000
35773	35800	0.00032	1436.11	5458	NaN	13000
35780	35790	0.00012	1436.04	3170	1900	5900
35742	35776	0.00040	1434.69	2970	NaN	NaN

Date_of_Launch	Anticipated_Lifetime	Contractor	Launch_Site	Launch_Vehicle	longitude_radians	Inclination_radians
41597	NaN	Los Alamos Nation	Wallops Island Fl	Minotaur 1	NaN	0.707033
36958	12	Alcatel Space Ind	Guiana Space Cent	Ariane 5	0.498466	0.001222
41165	NaN	Miltec	Vandenberg AFB	Atlas 5	NaN	1.127483
36755	9	Lockheed Martin A	Vandenberg AFB	Titan IV	NaN	1.186824
40119	3	Thales Alenia Spa	Plesetsk Cosmodro	Breeze KM	NaN	1.717404
40963	8	Space Technology	Xichang Satellite	Long March 3A	1.029744	0.032638
36721	12	Lockheed Martin M	Cape Canaveral	Atlas 2 AS	-1.269029	0.001222
38664	15	EADS Astrium	Sea Launch (Odyss	Zenit 3SL	-0.920836	0.040666
37580	12	Alcatel Space Ind	Cape Canaveral	Atlas 2 AS	0.445059	0.000349
41044	15	Lockheed Martin C	Guiana Space Cent	Ariane 5 ECA	2.300344	0.001396

(a) Subset of satellites data table showing 21 variables and 10 records

```
# FIRST GROUP OF DEPENDENT VARIABLES
cluster_view_1 ~ categorical(
  {0: 0.945, 1: 0.02, 2: 0.01, ...})
if (cluster_view_1 == 0)
  Eccentricity ~ norm(0.002, 0.01)
elif (cluster_view_1 == 2)
  Eccentricity ~ norm(0.075, 0.015)
elif (cluster_view_1 == 3)
  Eccentricity ~ norm(0.028, 0.017)
...

# SECOND GROUP OF DEPENDENT VARIABLES
cluster_view_2 ~ categorical(
  {0: 0.45, 1: 0.365, 2: 0.01, ...})
if (cluster_view_2 == 0)
  Power_watts     ~ norm(870.32, 877.80)
  Launch_mass_kg  ~ norm(442.08, 528.63)
  Dry_mass_kg     ~ norm(362.45, 321.64)
  Period_miniutes ~ norm(101.67, 56.02)
  Perigee         ~ norm(683.49, 56.02)
  Apogee          ~ norm(742.68, 2411.91)
elif (cluster_view_2 == 1)
  Power_watts     ~ norm(7157.58, 4629.09)
  Launch_mass_kg  ~ norm(3870.96, 1417.09)
  Dry_mass_kg     ~ norm(1921.21, 762.07)
  Period_miniutes ~ norm(1435.63, 57.13)
  Perigee         ~ norm(35820.37, 1434.57)
  Apogee          ~ norm(35701.83, 2548.60)
...
```

(b) Synthesized row generator

Figure 2: Synthesizing probabilistic programs that model heterogeneously typed cross-sectional data.

1 Example

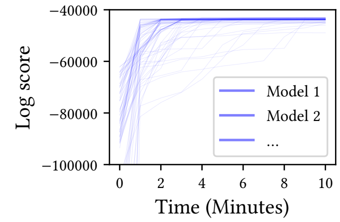
The InferenceQL system automates data analysis and machine learning tasks by allowing users to input data tables and queries and to automatically generate answers for them (Figure 1). It consists of a probabilistic program synthesis component [27] that creates generative model programs that are called *row generators*. The InferenceQL query planner and query engine use row generators to answer questions about the data and the domain by querying an underlying probabilistic model.

Figure 2 shows an example of probabilistic program synthesis, which takes a heterogeneously-typed data table of satellites (maintained by the Union of Concerned Scientists [32]) and returns a probabilistic program that models the data. Figure 3(a) shows the high-level interface to creating synthesizing programs. Users can then compare synthetic data (generated from the probabilistic programs) with observed data in order to develop intuition about what the model learned from the data, shown in Figure 3(b). InferenceQL can generate synthetic data from both marginal distributions and conditional distributions given a user-specified predicate (code box in Figure 3(b)). The two plots in Figure 3(b) illustrate a qualitative goodness-of-fit in the sense that distribution of synthetic (orange dots) samples appears to approximately match the observed data (black dots).

Data analysts can use the query language to search for probable anomalies and data-entry errors, shown in Figure 3(c). To find values for the column `Period_minutes` that the model considers

```
# Synthesize probabilistic
# programs given user-specified
# parameters in parameters.yaml
WITH LOAD 'parameters.yaml'
    AS params:
  BUILD default_model
  FOR satellite_data
  USING params;
```

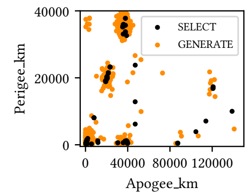
```
#---- (parameters.yaml) ----#
# PARAMETERS FOR MODEL BUILDING
strategy: Gibbs # or SMC
number_models_in_ensemble: 100
inference_minutes: 10
override_schema:
  Perigee_km: numerical
  Purpose:    nominal
```

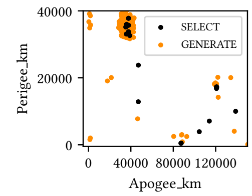


(a) Step 1: Synthesize probabilistic programs using the observed data table.

```
SELECT Perigee_km, Apogee_km FROM satellite_data INNER JOIN
  SELECT Perigee_km AS Perigee_km_generated, Apogee_km AS Apogee_km_generated
  FROM GENERATE Perigee_km, Apogee_km UNDER default_model;

SELECT Perigee_km, Apogee_km FROM satellite_data INNER JOIN
  SELECT Perigee_km AS Perigee_km_generated, Apogee_km AS Apogee_km_generated
  FROM GENERATE Perigee_km, Apogee_km GIVEN Period_minutes < 1000
   UNDER default_model
WHERE Period_minutes < 1000;
```

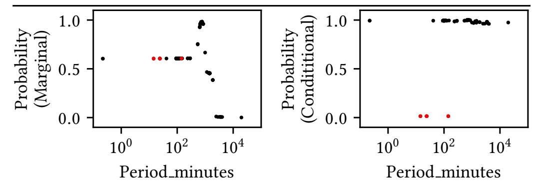




(b) Step 2: Compare synthetic data generated from the probabilistic programs to observed data.

```
WITH SELECT STDEV(Period_minutes) FROM satellite_data AS std_period:
  SELECT Period_minutes, Class_of_Orbit, Perigee_km, Apogee_km
  FROM satellite_data
  WHERE
      (PROBABILITY OF
        Period_minutes > (satellite_data.Period_minutes - std_period) AND
        Period_minutes < (satellite_data.Period_minutes + std_period)
          UNDER default_model)
      <
      (PROBABILITY OF
        Period_minutes > (satellite_data.Period_minutes - std_period) AND
        Period_minutes < (satellite_data.Period_minutes + std_period)
          GIVEN (* EXCEPT Period_minutes)
          UNDER default_model);
```

Period_minutes	Class_of_Orbit	Perigee_km	Apogee_km
23.9	GEO	35771.0	35805.0
142.0	GEO	35897.0	35909.0
14.3	GEO	35770.0	35803.0
23.9	GEO	35771.0	35805.0

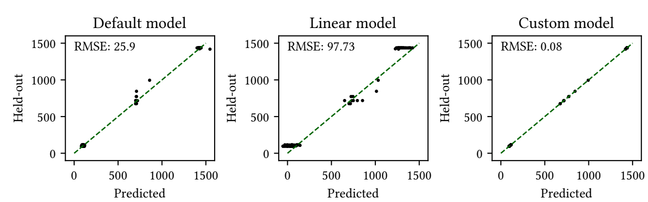


(c) Step 3: Search for probable anomalies, which include data entry errors.

```
WITH SELECT * FROM satellite_data
  WHERE rowid <= 1000 AS training_data:
    BUILD default_model FOR training_data AND
    BUILD linear_model  FOR training_data AND

WITH SELECT * FROM satellite_data
  WHERE rowid > 1000 AS test_data:
    SELECT
      period,
      (PREDICT period GIVEN Perigee_km, Apogee_km
        UNDER default_model)
      (PREDICT period GIVEN Perigee_km, Apogee_km
        UNDER linear_model)
      (PREDICT period GIVEN Perigee_km, Apogee_km
        UNDER custom_model)
    FROM test_data;
```

```
function keplers_law(apogee, perigee)
  GM = 398600.4418; earth_radius = 6378;
  a = (abs(apogee) + abs(perigee)) * 0.5 + earth_radius;
  return 2 * π * sqrt(a^3 / GM) / 60 end;
@gen function custom_model(Perigee_km, Apogee_km)
  out = {:Period} ~ normal(keplers_law(Perigee_km, Apogee_km), 0.01)
  return out end;
```



(d) Step 4: Customize probabilistic programs using an orbital model from physics.

Figure 3: A representative data analysis workflow in InferenceQL on the satellites data.

improbable in light of the data, the query (left code box) produces the result by comparing the probability of the value for `Period_minutes` marginally and conditionally in the `WHERE` clause. The only rows returned are those whose conditional probability is lower than the marginal; the corresponding `Period_minutes` values are highlighted in red in the table and plots of Figure 3(c).

Finally, users with domain expertise can customize probabilistic programs. Figure 3(d) shows an example custom orbital model from physics. To quantitatively assess the goodness-of-fit, we first split the data into training and test data and build three models: the automatically synthesized default model, a generalized linear model (GLM), and a custom probabilistic program for noisy orbital physics. We then predict a column in the held-out data set. The default model predicts more accurately than the GLM (4x more accurate via root mean square error (RMSE)) and the custom probabilistic program beats the default (a further 300x improvement in RMSE).

Table 1: Generative modeling benchmark.

	Jensen-Shannon Divergence			
Dataset	InferenceQL	CTGAN	Copulas	TVAE
Nursery	0.04	0.14	0.29	0.05
Tumor	**0.06**	0.40	0.20	0.45
Flare	**0.05**	0.22	0.23	0.28
Car	0.05	0.16	0.12	0.08
Mushroom	**0.08**	0.15	0.33	0.11
Soybean	**0.10**	0.18	0.22	0.36
Breast-cancer	**0.15**	0.38	0.43	0.38
Heart-disease	**0.08**	0.16	0.30	0.44
Connect-4	**0.04**	0.10	0.22	0.08
Chess	**0.03**	0.10	0.17	0.05

Table 2: Anomaly detection benchmark.

		Anomaly Detection Accuracy	
Dataset	Target	InferenceQL	GLM
Abalone	Rings	86%	82%
Breast-cancer	class	100%	60%
Heart-disease	num	97%	47%

Table 3: Runtime optimization benchmark.

		InferenceQL (SPPL backend)		**Python API (SPPL)**
Dataset	Target	Independence Analysis	Default Optimization	Default Optimization
Nursery	Evaluation	11.14 ± 7.31	501.35 ± 571.08	302.29 ± 366.1
Tumor	Type	1.99 ± 0.34	3.21 ± 0.51	3.24 ± 0.8
Flare	Num_common_flares	6.96 ± 2.56	14.32 ± 14.27	8.84 ± 7.78
Car	Evaluation	13.03 ± 4.69	153.91 ± 275.4	92.3 ± 158.98
Mushroom	Edible?	31.34 ± 6.17	34.07 ± 6.87	24.74 ± 5.78
Soybean	Disease	9.44 ± 3.05	11.7 ± 2.26	9.05 ± 2.19
Breast-cancer	Diagnosis	5.07 ± 0.71	6.78 ± 0.73	3.93 ± 0.82
Heart-disease	Present?	3.49 ± 1.49	11.61 ± 8.11	8.99 ± 6.02
Connect-4	White_can_win	34.24 ± 24.61	65.26 ± 59.99	44.61 ± 36.0
Chess	Outcome	61.83 ± 45.34	86.27 ± 51.3	62.79 ± 34.56

2 Experiments

We now report experiments evaluating InferenceQL against statistical and neural baselines.

Generative modeling benchmark. Table 1 shows the average Jensen-Shannon divergence between (discretizations of) the observed data and learned generative models, for all pairwise marginals in 10 datasets from the UCI machine learning repository [8], according to simulations from InferenceQL, Gaussian copulas [23], CTGAN [34], and TVAE [34]. The bold entries indicate statistically significant lowest error under a Bonferroni corrected Mann-Whitney U test, which are achieved by InferenceQL in 8 of 10 benchmark problems and zero times by other techniques.

Anomaly detection benchmark. Table 2 shows that InferenceQL detects a higher percentage of anomalies than does a GLM baseline on three datasets from the UCI repository. Anomalies were inserted into a target column by flipping the class label in each row with probability 0.05 and detected using a query similar to the one in Figure 3(d).

Query optimization. The InferenceQL query planner contains a built-in optimization for querying row generators specified in the SPPL language [28]. Table 3 shows the runtime of InferenceQL queries for computing the conditional probability of all cell values in one target column given all the other values in the same row, for 10 datasets from the UCI repository. The third column shows the runtime using InferenceQL's independence analysis optimization, which statically eliminates from the query all conditioning variables that are structurally independent of the target variable. The fourth column shows the runtime using InferenceQL without independence analysis and the final column shows the runtime using the Python API to SPPL, which both do not automatically leverage independence analysis and are slower in cases where independencies can be exploited.

3 Related Work

Many AutoML systems have been developed for tabular data; prominent examples include Amazon's AutoGluon-Tabular [9] and SageMaker Autopilot [7], Google Cloud Platform AutoML Tables [17], Uber's Ludwig [21], H2O AutoML [16], and a number of earlier systems such as Auto-WEKA [31], auto-sklearn [10], hyperopt-sklearn [2], TPOT [22], autoxgboost [30], ML-Plan [20], OBOE [35], GAMA [12], and Auto-Keras [15]. A survey and comparison of many of these systems can be found in Erickson et al. [9, §3]. In contrast to these systems, which typically emphasize discriminative ML, InferenceQL provides users with generative models that can be queried repeatedly to answer a wide range of questions about the data.

The BayesDB probabilistic programming system [19] is closely related to InferenceQL, but more limited. BayesDB and InferenceQL both provide automatic Bayesian model discovery, suitable for exploratory data analysis, predictive modeling, and inferential statistics from sparse, heterogeneously-typed data tables. But InferenceQL is often more scalable than BayesDB, due in part to its use of sum-product expressions [28] (a class of probabilistic circuits [6]) to implement query plans and enable automated query optimizations. InferenceQL can be used to query custom models in the Gen probabilistic programming language [5], leveraging Gen's support for pseudo-marginal approximations to the composable generative population model interface [24]. InferenceQL also provides a more compositional and expressive query language than BayesDB, including support for SQL-like inlining of column transformations and predicates. Together, these improvements allow InferenceQL users to interleave SQL and inference operations in complex end-to-end Bayesian AutoML workflows.

Probabilistic databases have been developed for querying noisy or uncertain data [29, 33]; for a survey of several probabilistic database systems, see [33, §6.2]. Other classes of database systems that integrate probability in some form include databases that use probabilistic circuits to improve query performance [13] and database systems extended by functions for imputation [4], time series prediction [1], random data generation [14] and simulation [3]. Unlike InferenceQL, these systems do not provide automated Bayesian model discovery, custom probabilistic programming, or compositional SQL-like queries that interleave SQL with Bayesian inference.

4 Conclusion

Limitations. It is unclear how to tune InferenceQL to compete with traditional non-Bayesian AutoML systems on discriminative ML problems. In principle, InferenceQL can use SPPL encodings of decision-tree classifiers [28] to match the accuracy of typical ML deployments. Currently, users can only achieve this awkwardly, via manual customization of the underlying models. It is unclear when and how InferenceQL should switch from Bayesian to non-Bayesian AutoML methods. Also, the current InferenceQL prototype only supports cross-sectional data tables. It would be conceptually straightforward and worthwhile in practice to integrate domain-general Bayesian structure learning methods for multivariate time series [25] or relational systems [26].

Broader Impact. If maximally successful, InferenceQL could enable typical SQL database users to apply Bayesian inference and probabilistic programming. InferenceQL could significantly reduce the cost and improve the quality of Bayesian data analysis, for both experts and novices, and help to make Bayesian approaches more routinely applicable, potentially improving the quality of data analysis. InferenceQL could also help reduce the risk associated with data breaches and data sharing, by enabling broader use of synthetic data.

Potential harms include reduced cost for invasive, abusive, or manipulative applications of modeling, by governments, corporations, and other actors — which may, in turn, cause people to steal sensitive data or surveil more.

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