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# Creating a calibration chain for measuring instruments using relational database

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**Abstract**

One of the indicators of measurement quality is metrological traceability, which is represented in the form of calibration chains, that are documented sequences of calibration results from the working measuring instrument to the measurement standards with the highest accuracy.

Based on conducted analysis, it is proposed to present calibration chains not linearly but as branched acyclic directed graphs.

The aim of the study is to find a solution for calibration data storage and calibration chain creation for a particular measuring instrument using stored calibration data to ensure metrological traceability in a simple way.

To store the information about measuring instruments and their calibrations, relational databases are proposed to be used. They provide consistent data and allow obtaining historical data about calibrations. In addition, an algorithm to create documented calibration chains for branched traceability chains is proposed.

The practical value of the study lies in the development of a software product for measuring instruments of gas volume and volumetric gas flow rate. The software application will give the possibility to metrological centre "Ivano-Frankivskstandartmetrology" to keep consistent calibration data and to ensure metrological traceability for particular measuring instruments to the national measurement standards.

**Keywords:** calibration chain; measuring instruments; relational database; directed acyclic graph.

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## Introduction

The highest accuracy of physical quantities reproducing is ensured by national measurement standards, which transfer the values of such quantities to working measurement standards, and these, in turn, transfer the values to working measuring instruments. Only by following such a sequence, a high level of accuracy of measurements results of working measuring instruments can be ensured. Such sequence is documented and called a calibration chain, the main features of which are continuity, linearity, or branching. The relation between measurement result obtained with a measuring instruments and measurement standards is called metrological traceability.

Metrological traceability is a key aspect of ensuring measurement accuracy and confidence in the measuring results obtained. It is based on a continuous calibration chain, which links measurement results with high accuracy measurement standards through a documented sequence of calibrations [1]. That is why the problem of creating continuous calibration chains and ensuring metrological traceability is relevant.

## Recent studies and publications

The calibration chain is mostly a linear chain, but if during calibration of specific measuring instruments several references are used, the calibration chain becomes branched [2] and looks like a typical graph.

This statement is applicable for calibration of gas meters and gas flow meters, since for gas volume calculation gas parameters are required in accordance with the ideal gas law. [3]. For a gas meter, as a result of calibration, an error against flow rate will be obtained with appropriate uncertainty of measurements. The error of the gas meter δ is calculated by [4]:

$$\delta = \left( \frac{N_m / K_m}{V_s} \cdot \frac{T_s}{T_m} \cdot \frac{P_m}{P_s} - 1 \right) \cdot 100\%, \tag{1}$$

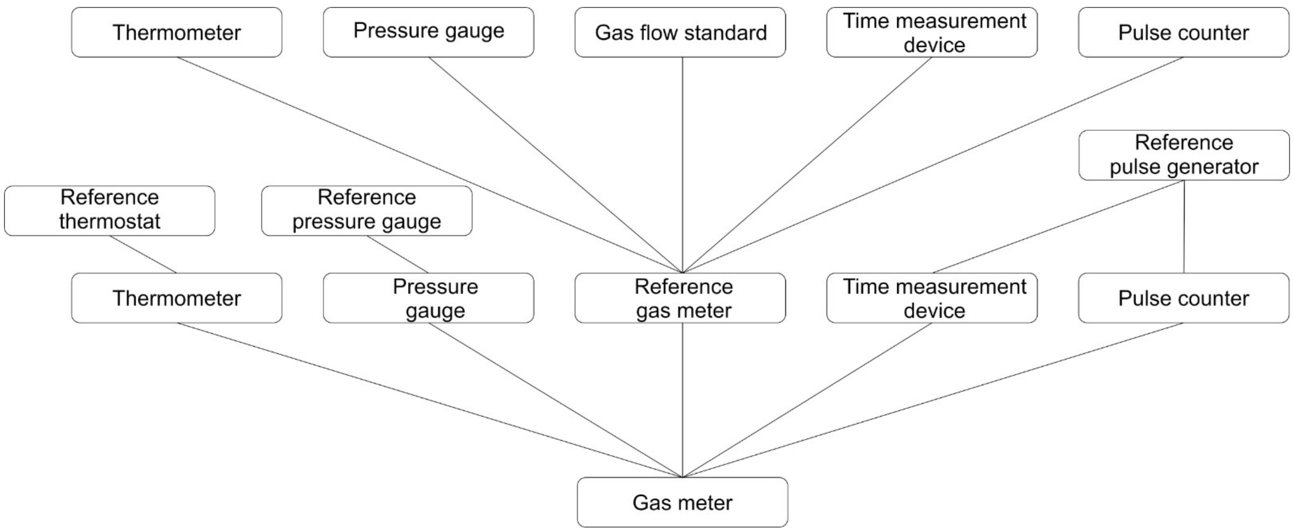


Fig. 1. Graph that represents gas meter calibration chain

where $N_m$ is the number of pulses from calibrated gas meter; $K_m$ is the gas meter $K$-factor, pulses/m$^3$; $V_s$ is the gas volume measured by a measurement standard, m$^3$; $T_s$, $T_m$ are temperatures of the measurement standard and gas meter, °C; $P_s$, $P_m$ are gauge gas pressures of the measurement standard and gas meter, Pa.

As it can be seen from formula (1), there are several quantities that should be measured during the gas meter calibration and therefore all measuring instruments for appropriate quantities should be calibrated.

In [5], the calibration chain for gas meter and gas flowmeters in Ukraine is described, but it was simplified to linear form, as well as it does not include all measuring instruments for gas parameters such as pressure, temperature, and measuring instruments for measuring time intervals and pulses from gas meters, which are required according to formula (1). On the other side, in [6], a more accurate calibration chain is described, which include branches for appropriate measuring quantities (see formula 1). So, this chain can be represented as an acyclic directed graph (see Fig. 1).

A feature of the graph presented on Fig. 1 is that it is acyclic and directed because low accuracy measuring instruments cannot be used as references for calibration of higher accuracy instruments, and measuring instruments cannot be used to calibrate themselves. The nodes of such a graph are measuring instruments, and edges represent calibrations themselves.

Most metrological centres, both domestic and foreign ones, usually keep calibrations related information in the paper form or in Excel files, which does not allow clear confirmation and reproduction of calibration chains for specific measuring themselves. But even for metrological institutes which store calibration data in databases [7], there is no information regarding the possibility to reproduce calibration chains using stored calibration data in a simple way. That is, the customer cannot check whether this device is traceable to national or international measurement standards.

The aim of this study is to find a solution for calibration data storage and calibration chain creation for specific measuring instruments to ensure metrological traceability using stored calibration data in a simple way.

**Creating a calibration chain using recursive SQL query**

The described above task can be addressed using a relational database, which is frequently used for calibration data storage [7]. For this study, PostgreSQL relational database was used. It is necessary to impose several restrictions at the database level to avoid inconsistent data, as well as to eliminate data manipulation.

Let us describe the database schema used in this study.

Database schema includes several entities, such as measuring device (Device) and calibration itself (Calibration) as an event. Since the reference or measurement standard is essentially a measuring instrument, which is also subject to calibration, we store information related to measurement standards in the Device table as well. At the same time, an auxiliary table Calibration Standards is used to store information about the standards used in calibration, which helps to implement a ManyToMany relationship between Calibration and Device entities. The Fig. 2 shows simplified database schema for calibration results storage.

To ensure data integrity and consistency and to satisfy the calibration logic, several requirements and restrictions shall be imposed:

1. Measuring instrument serial number and device name shall be unique across the whole database.

2. Measurement standards used for calibration shall have higher accuracy than the accuracy of a calibrated measuring instrument.

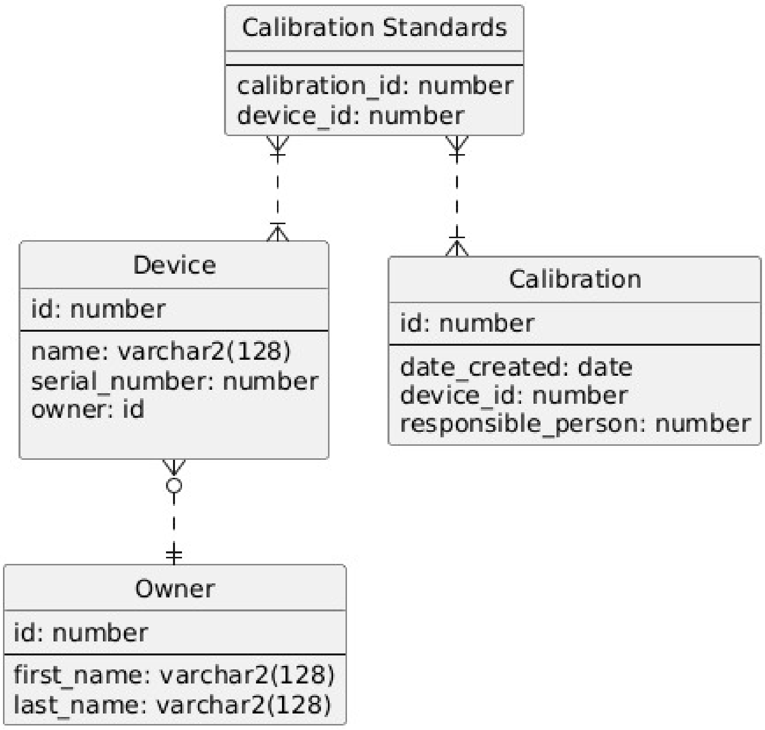


Fig. 2. Simplified database schema for calibration results

3. Measuring instruments cannot be used to calibrate themselves.

The first restriction is observed by using composite unique index. Other restrictions are implemented on the application level through the appropriate conditions.

Given that, as mentioned above, the calibration chain is a directed acyclic graph, obtaining data from the database that corresponds to the calibration chain for a particular measuring instrument consists in searching all nodes and edges in the graph starting from the node of a particular measuring instrument to the measurement standards with the highest accuracy. The described task can be solved by using the Depth-First Search (DFS) algorithm, well known from linear algebra [8].

To implement this algorithm in a relational database, it is better to use a recursive algorithm with Common table expression (CTE). Such recursive query simulates graph DFS algorithm [9]. Given that the algorithm is recursive, to limit the depth of recursion, we start traversing the graph from a particular measuring device with identifier *device_id* (see on page 6). As a result, the SQL query was developed to create a calibration chain for a particular measurement instrument with identifier *device_id*.

In the SQL query presented above, besides described above entities attributes, a calculated field *level* was also used, which represents a level in the calibration chain. The first part of the query gets information about a calibrated device, that is level zero. On each recursive step, the information about the measurement standards used for calibration is received, which is subsequently joined with the result. The step shall be repeated until the last measurement standards with the highest accuracy are reached.

**Query performance analysis**

During the study, much attention was paid to the developed SQL query performance.

Since the query is developed for a particular instrument, it does not depend on the number of records in the whole database. But the main dependency is the recursion depth, which is equal to the number of calibrations in the calibration chain. Let us assume that for each calibration three measurement standards are used, and the calibration chain has no more than six levels. In such a case, the average number of records to process amounts to 300 to 1000. So, even in a database with about 1 million records, a SQL query will process only no more than 1000 records.

For SQL query optimization, database indexes were used for fields used in JOIN operations, in particular, *device_id*, *calibration_id* and *date_created*. In addition, since there is data ordering by date, a composite index for *device_id* and *date_created* was used. This enabled to avoid a complete record search and achieve computational complexity O(log $N$), where $N$ is the number of to be processed records.

For testing purposes, a test dataset with 100 thousand records was used. For all devices in test records, different numbers of calibrations and different depth of the chains were used.

Testing results described in Table 1.

Testing results show the acceptable level of SQL query performance, so the proposed solution can be used in real life cases.

```
WITH RECURSIVE traceability(id, name, serial_number, level) AS (
    SELECT d.id, d.name, d.serial_number, 0 AS level
    FROM device d
    WHERE d.id = %(device_id)s

    UNION ALL

    SELECT d2.id, d2.name, d2.serial_number, t.level + 1 AS level
    FROM traceability t
    JOIN (
        SELECT DISTINCT ON (ms.device_id)
            ms.device_id,
            ms.calibration_id
        FROM calibration_standards ms
        JOIN calibration s ON ms.calibration_id = s.id
        ORDER BY ms.device_id, s.date_created DESC
    ) latest_ms ON latest_ms.calibration_id = (
        SELECT id
        FROM calibration
        WHERE device_id = t.id
        ORDER BY date_created DESC
        LIMIT 1
    )
    JOIN device d2 ON d2.id = latest_ms.device_id
)
SELECT DISTINCT id, name, serial_number, level
FROM traceability;
```

Table 1

Testing results for recursive SQL query to create a calibration chain

| Number of calibrations at level | Number of levels | Approximate number of records in graph | Query duration (ms) |
|---|---|---|---|
| up to 3 | up to 6 | ~200–500 | ~50–300 |
| up to 3 | up to 4 | up to 40 | ~10–50 |
| up to 5 | up to 4 | up to 781 | ~50–200 |
| real case for gas meter calibration up to 5 | up to 3 | up to 173 | ~30–120 |

**Summary**

As a result of the presented study, the database scheme and SQL query were developed to store calibration data in relational databases and create continuous calibration chains for measuring instruments with branched traceability chains. The solution will help metrological centres to keep consistent calibration data and to ensure metrological traceability for specific measuring instruments, and the end user will be able to verify whether his measuring instrument is traceable to national measurement standards.

The proposed solution was used for the software application development for State Enterprise "Ivano-Frankivskstandartmetrology", primarily for gas flow measuring instruments. Currently, the developed software application is undergoing testing.

# Побудова ланцюга калібрування засобів вимірювання з використанням реляційної бази даних

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**Анотація**

Одним із показників точності вимірювань є метрологічна простежуваність, яка відображається у вигляді ланцюга калібрувань, що є задокументованою послідовністю між результатами вимірювань засобу вимірювання та еталонами вищого рівня точності.

На основі проведеного аналізу для засобів вимірювання, при калібруванні яких використовується кілька еталонів, запропоновано застосовувати не лінійний ланцюг калібрування, а розгалужений у вигляді графа. Для прикладу, калібрувальний ланцюг для лічильників та витратомірів газу повинен бути розгалуженим, тому що має охоплювати всі засоби для властивостей газу: тиск, температуру, засоби вимірювання часових інтервалів та імпульсів.

Метою роботи є пошук рішення для зберігання даних про калібрування засобів вимірювання та побудови за цими даними ланцюга калібрувань для конкретного засобу вимірювання для забезпечення простежуваності в простий спосіб.

У більшості вітчизняних і закордонних метрологічних центрів існує практика надавати й зберігати інформацію у паперовому вигляді чи в Excel таблицях, але це не дає змоги чітко підтвердити й відтворити ланцюг калібрування для певного засобу вимірювання. Тому запропоновано рішення формувати калібрувальні дані з використанням реляційної бази даних PostgreSQL для зберігання інформації про засоби вимірювання та їхні калібрування. При цьому забезпечується узгодженість даних, а також є можливість отримання історичних даних про калібрування.

Крім того, для побудови документованого ланцюга калібрування до еталона найвищої точності для розгалужених ланцюгів простежуваності запропоновано використовувати відомий із лінійної алгебри алгоритм DFS (Depth-First Search) – "Пошук у глибину".

Практичне значення полягає в розробленні програмного продукту для засобів вимірювання об'єму та об'ємної витрати газу. Вказане програмне забезпечення дасть можливість метрологічній установі ДП "Івано-Франківськстандартметрологія" зберігати свої калібрувальні дані в узгодженій формі й дозволить забезпечити метрологічну простежуваність конкретних засобів вимірювання до національних еталонів.

**Ключові слова:** ланцюг калібрувань; засіб вимірювання; реляційна база даних; ациклічний спрямований граф.

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