南開大學
Nankai University

南　开　大　学

网络空间安全学院

数据安全实验报告

交互式发布 DP 方案评估

2111408 周钰宸

年级：2021 级

专业：信息安全

指导教师：刘哲理

2024 年 5 月 15 日

摘要

差分隐私概念最早由于 2006 年提出, 差分隐私并不是要求保证数据集的整体性的隐私, 而是对数据集中的每个个体的隐私提供保护。

本次实验基于差分隐私的拉普拉斯交互式发布机制，完成了 DP 方案设计，指定隐私预算为 0.1，支持查询次数为 20 次，对 DP 发布后的结果进行评估，说明隐私保护的效果。

最后对隐私保护效果和数据可用性的 `Trade-off` 之间进行了探索性讨论，加深了对隐私保护相关理论知识和研究成果的实践性理解与认知。

关键字：数据安全　差分隐私　拉普拉斯机制　交互式发布方案

目录

一、 实验要求

实验目的

1. **实验 5.1：**对某类数值型数据统计查询的基于拉普拉斯机制的防护方案。

   实验内容：对一个数据集（zoo.csv）进行统计查询，该数据集描述了一个动物园喂食的场景，第一列中数据为动物名称，第二列中数据为动物每天消耗的胡萝卜数量。查询定义为“每日进食超过 55 根胡萝卜的动物数量”。请设计相关的隐私保护方案，确保查询过程不泄露信息。

2. **参考教材实验 5.1，**对交互式发布方案进行 DP 方案设计，指定隐私预算为 0.1，支持查询次数为 20 次，对 DP 发布后的结果进行评估，说明隐私保护的效果。

本次实验参考上述实验要求完成了对交互式发布方案进行 DP 方案设计与结果的评估，并对隐私保护的效果进行了详尽的分析。最后我还拓展性地探索了在数据可用性和隐私保护效果之间的 `Trade-off` 的方式，加深了对隐私保护相关理论知识和研究成果的实践性理解与认知。

二、 实验原理

(一) 差分隐私

差分隐私（Differential Privacy）是一种确保个体数据隐私的统计技术。在保护数据隐私的同时，它允许对数据集进行分析和处理。差分隐私的核心思想是通过添加噪声来模糊个体数据的影响，从而保护个人隐私。

差分隐私的定义可以用以下公式表示：对于任何两个相邻数据集 D 和 D'，以及任意的查询函数 Q，差分隐私保证查询结果 $Q(D)$ 和 $Q(D')$ 的分布几乎相同。具体而言，对于任何可能的输出集合 S，有：

$$\Pr[Q(D) \in S] \leq e^{\epsilon} \cdot \Pr[Q(D') \in S] + \delta$$

其中，ϵ 是隐私预算（Privacy Budget），δ 是允许的概率差距。

这种方法通过以下几种方式实现：

- 添加噪声：在查询结果中加入随机噪声，使得攻击者难以确定个体数据。
- 随机响应：对数据进行随机处理，以增加不确定性。
- 平滑敏感度：通过平滑数据的敏感度来减少隐私泄露的风险。

差分隐私广泛应用于各种数据发布和分析任务中，例如统计分析、机器学习和数据库查询等领域。它为数据隐私保护提供了一种系统化、理论化的方法。**也是本次实验的重要理论基础。**

(二) 交互式数据发布方案

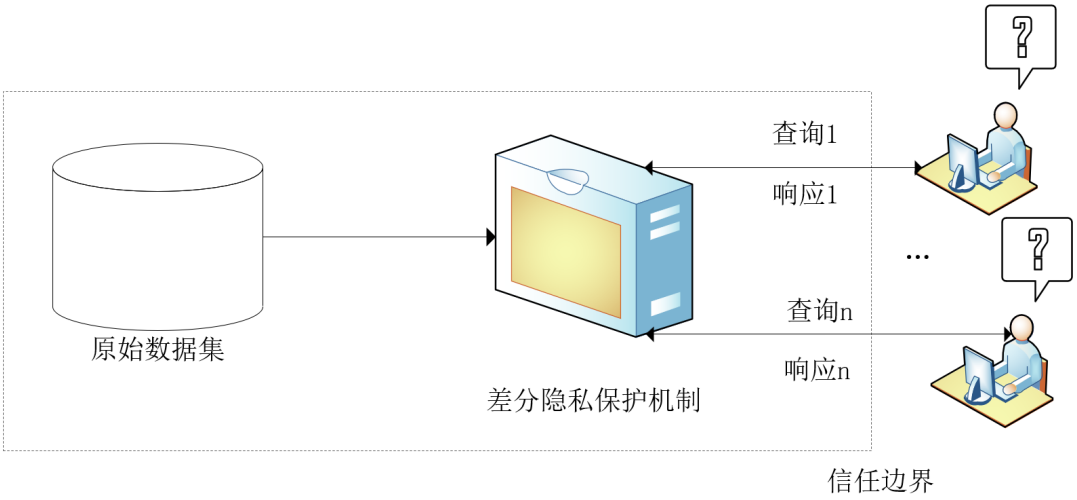

图 1: 交互式数据发布方案

如图1所示，交互式数据发布方案是一种允许用户与数据系统交互以获取统计信息的方法。在这种方案中，用户可以向系统提交查询，系统会根据预设的隐私保护机制返回相应的结果。

交互式数据发布的主要特点包括:

- **实时响应**：用户可以根据需要随时提出查询，系统实时计算并返回结果。
- **动态保护**：每次查询时，系统会根据当前的隐私预算动态调整噪声的大小，以确保整体隐私预算不被超出。
- **查询控制**：系统可以设置查询限制，如最大查询次数、查询类型等，以防止隐私预算被迅速耗尽。

交互式数据发布方案通常包含以下几个步骤:

1. **用户查询**：用户向系统提交查询请求，指定需要获取的信息。
2. **噪声添加**：系统根据预设的差分隐私机制，在查询结果中添加适当的噪声。
3. **结果返回**：系统将加噪后的查询结果返回给用户。
4. **隐私预算更新**：系统更新当前的隐私预算，以反映已经消耗的隐私资源。

这种交互式方案的优势在于其灵活性和实时性，适用于需要频繁查询和动态数据分析的场景。然而，其隐私保护效果依赖于合理的隐私预算管理和噪声添加策略。

在实际应用中，交互式数据发布方案被广泛应用于统计分析、数据挖掘和机器学习等领域，能够在提供数据分析功能的同时，确保个体数据的隐私安全。

(三) 拉普拉斯机制

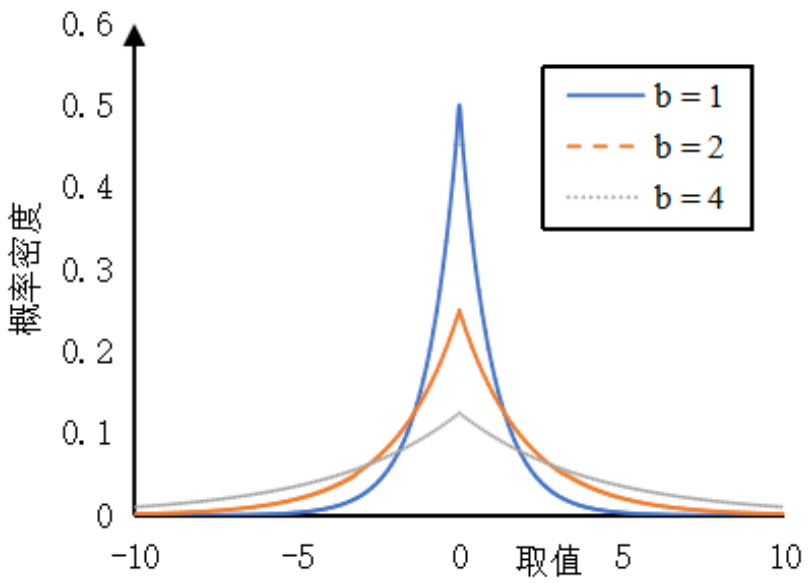

图 2: 拉普拉斯机制概率分布图

拉普拉斯机制（Laplace Mechanism）是一种常用的差分隐私实现方法。它通过在查询结果中添加拉普拉斯噪声来保护数据隐私。拉普拉斯机制的核心在于利用拉普拉斯分布来生成噪声，从而使得数据集的敏感信息得以隐藏。

拉普拉斯分布的概率密度函数（PDF）定义如下：

$$Lap(x|b) = \frac{1}{2b} \exp\left(-\frac{|x|}{b}\right) \tag{1}$$

如图2所示，拉普拉斯分布的形状是一种尖峰状，中心在原点，两侧对称。参数 b（尺度参数）控制了分布的宽度，值越大，分布越宽，噪声越大。

在拉普拉斯机制中，添加的噪声 z 是从拉普拉斯分布中抽样得到的，通常表示为 $z \sim Lap(0, b)$。具体实现步骤如下：

1. **计算敏感度**：确定查询函数 f 的全局敏感度 $S(f)$，即任意相邻数据集 D 和 D' 上 $f(D)$ 和 $f(D')$ 的最大差值。
2. **确定噪声尺度**：根据隐私参数 ϵ 和敏感度 $S(f)$，计算噪声尺度 $b = \frac{S(f)}{\epsilon}$。
3. **添加噪声**：在查询结果中添加噪声 z，即 $f(D) + z$，其中 $z \sim Lap(0, b)$。

通过添加拉普拉斯噪声，拉普拉斯机制能够有效隐藏个体数据在查询结果中的影响，从而保证差分隐私。

拉普拉斯机制的优点在于其实现简单、计算效率高，适用于各种统计查询和数据分析任务。它广泛应用于保护统计数据发布、机器学习模型训练和其他需要数据隐私保护的领域。

三、 实验准备

(一) 实验环境

虚拟机软件	VMware Workstation 17 Pro
虚拟机操作系统	Ubuntu 20.04.6 LTS amd64
实验工具 1	gcc version 11.4.0 (Ubuntu 11.4.0-1ubuntu1 22.04)

表 1: 本次实验环境及工具

(二) 实验项目框架

/Lab05
- include/ 包含有本次实验的两组成员函数文件使用的头文件
  - laplace.h 为 *laplace* 函数族提供函数定义
  - csvpackage.h 为 *csvpackage* 函数族提供函数定义
- testraw.c 数据集直接加噪实验部分的主函数放置于此，提供了数据集读取，给定隐私预算的噪音生成和加噪后结果展示的功能
- testhist.c 数据集直方图发布加噪实验部分的主函数放置于此，提供了数据集读取，给定隐私预算的噪音生成和加噪后统计值输出的功能
- laplace.c 为实验代码生成拉普拉斯分布的随机数，用于加噪
- csvpackage.c 实验代码的 *csv* 读取和预统计函数实现,针对样例代码提供读取为 *Animals* 结构体的功能
- zoo.csv 本次实验使用的样例数据集。其描述了一个动物园喂食的场景，第一列中数据为动物名称，第二列中数据为动物每天消耗的胡萝卜数量
- zoo_nb.csv 将 *zoo.csv* 中 "*Dugeng*" 项去除得到的相邻数据集
- medicaldata.csv 本次实验直方图发布部分的样例数据集。其描述了一个简单的医疗数据场景：假设其建立于某医疗数据集之上，其第一列数据为一年龄区间，第二列数据为该年龄区间患有某种疾病的人数。要发布的直方图即是以第一列数据为直方图的桶 (*Bucket*) 发布的统计数据
- md_nb.csv 将其中 "*30-40*" 区间的统计值*-1*，模拟原始医疗数据集内一名患者退出数据共享
- Makefile 用于编译使用的编译规则文件

四、 实验准备

(一) 安装必备项

首先在进行真正开始实验前，首先对实验环境进行搭建。先通过如下两个命令查看 Ubuntu 的 Linux 虚拟机信息与对必要项进行安装。

```
1 uname -a
2 sudo apt-get install build-essential
```

运行结果如下：]

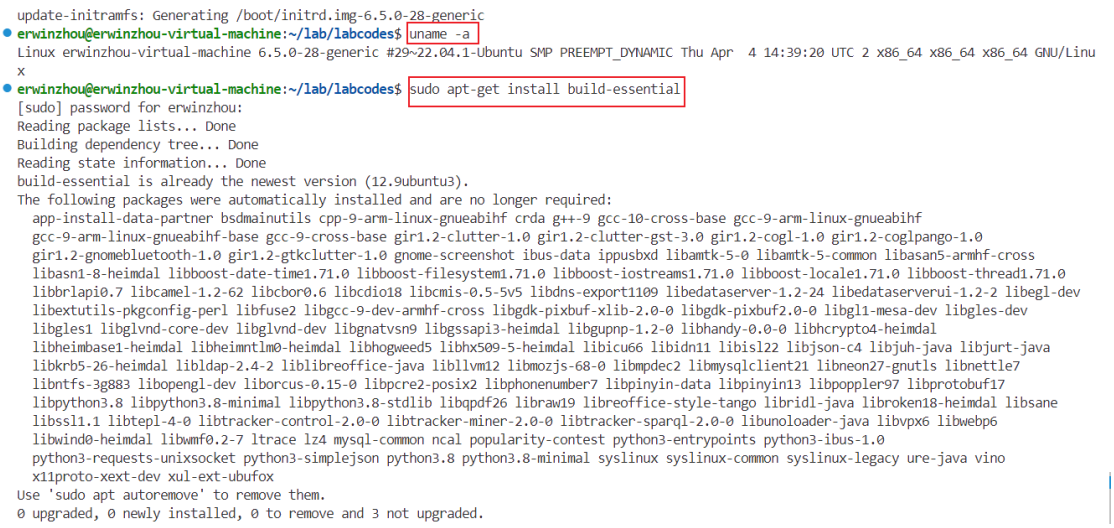

图 3: build-essential

如图3所示,可以看到我的 Ubuntu 的 Linux 虚拟机版本信息与构建信息。build-essential 已经是最新版本了。

```
erwinzhou@erwinzhou-virtual-machine:~/lab/labcodes$ uname -a
Linux erwinzhou-virtual-machine 6.5.0-28-generic #29~22.04.1-Ubuntu SMP
  ↪ PREEMPT_DYNAMIC Thu Apr 4 14:39:20 UTC 2 x86_64 x86_64 x86_64 GNU/Linux
erwinzhou@erwinzhou-virtual-machine:~/lab/labcodes$ sudo apt-get install
  ↪ build-essential
[sudo] password for erwinzhou:
Reading package lists... Done
Building dependency tree... Done
Reading state information... Done
build-essential is already the newest version (12.9ubuntu3).
The following packages were automatically installed and are no longer required:
/* blablabla */
0 upgraded, 0 newly installed, 0 to remove and 3 not upgraded.
```

而后通过命令 gcc -v 查看将要使用的 GCC 编译器版本:

图 4: GCC 查看版本信息

如图4所示，运行结果为:

```
erwinzhou@erwinzhou-virtual-machine:~/lab/labcodes$ gcc -v
Using built-in specs.
COLLECT_GCC=gcc
COLLECT_LTO_WRAPPER=/usr/lib/gcc/x86_64-linux-gnu/11/lto-wrapper
OFFLOAD_TARGET_NAMES=nvptx-none:amdgcn-amdhsa
OFFLOAD_TARGET_DEFAULT=1
Target: x86_64-linux-gnu
Configured with:
/* blablabla */
Supported LTO compression algorithms: zlib zstd
gcc version 11.4.0 (Ubuntu 11.4.0-1ubuntu1~22.04)
```

(二) 解压文件

然后将本次实验文件 experiments.tar.gz 通过命令 tar -xzvf ./experiments.tar.gz 解压即可。解压结果如下:

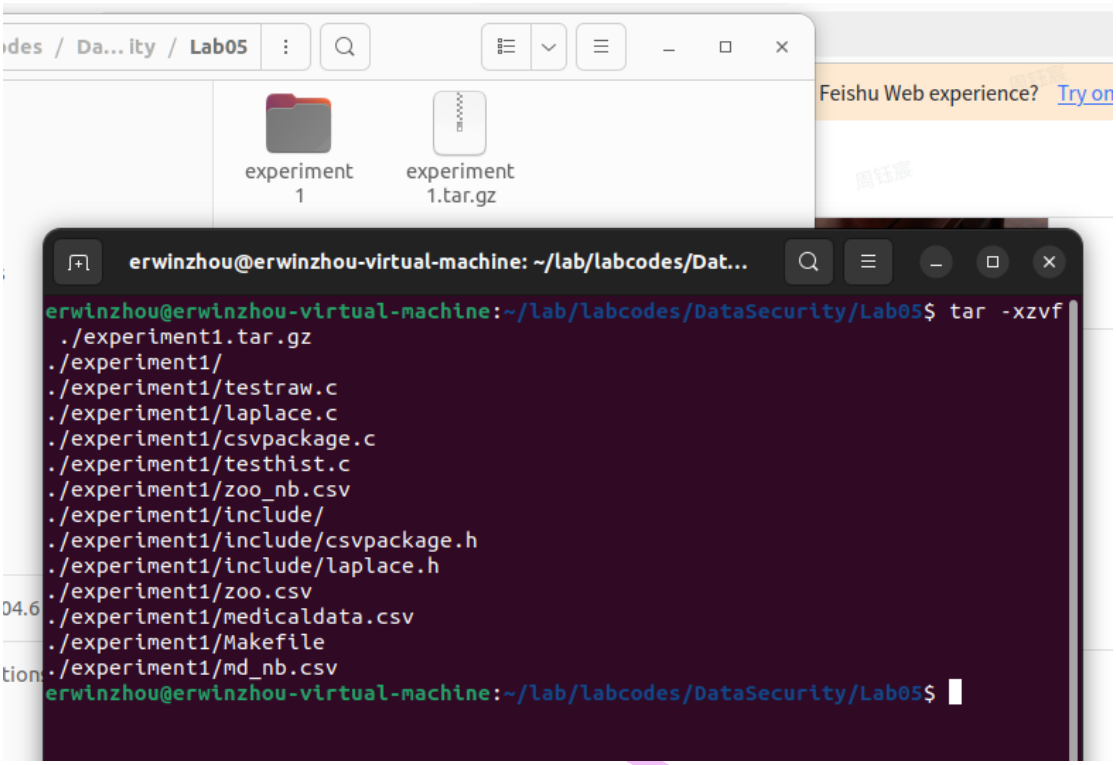

图 5: 解压文件结果

如图5所示，可以看到已经完成了解压。

(三) 修改代码问题

我注意到如果直接通过 make 命令进行编译，会出现编译错误的结果：

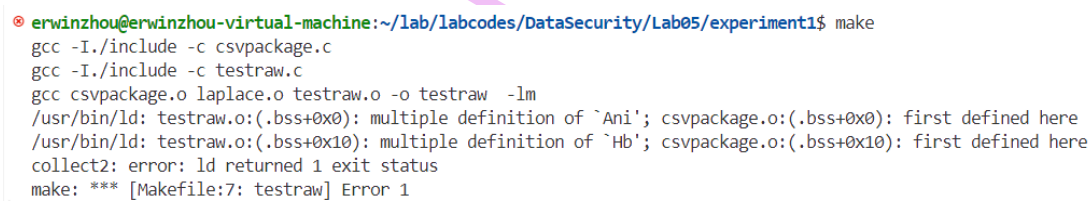

图 6: make 编译失败

如图6所示，提示信息为：

```
erwinzhou@erwinzhou-virtual-machine:~/lab/labcodes/DataSecurity/Lab05/experiment1$ make
gcc csvpackage.o laplace.o testraw.o -o testraw  -lm
/usr/bin/ld: testraw.o:(.bss+0x0): multiple definition of `Ani'; csvpackage.o:(.bss+0x0): first defined here
/usr/bin/ld: testraw.o:(.bss+0x10): multiple definition of `Hb'; csvpackage.o:(.bss+0x10): first defined here
collect2: error: ld returned 1 exit status
```

```
make: *** [Makefile:7: testraw] Error 1
```

经过查看是因为实现文件 testraw.c 和 csvpackage.c 中都包含了 csvpackage.h，而该头文件中对 Animals 结构体实例 Ani 和 Histobuckets 结构体实例 Hb 都进行了定义。

经过思考,我将 Animals 结构体实例 Ani 和 Histobuckets 结构体实例 Hb 在 csvpackage.h 中声明不定义，在 csvpackage.c 定义，在 testraw.c 中直接引用:

```c
                /* 在 csvpackage.h 中 */
/*
结构体: ^^IAnimals
为 zoo 数据集提供结构化存储功能
成员说明:
name^^I^^I 对应 zoo 数据集的第一列，动物名称
carrots^^I^^I 对应 zoo 数据集的第二列，每日食用胡萝卜数量
*/
struct Animals
{
    char *name;
    int carrots;
};

/*
结构体: ^^IHistobuckets
为 medicaldata 数据集提供结构化存储功能
成员说明:
bucket^^I^^I 对应 medicaldata 数据集的第一列，分桶名称
count^^I^^I 对应 medicaldata 数据集的第二列，桶内元素数量
*/
struct Histobuckets
{
    char *bucket;
    int count;
};

/* Only to declare but not to define, in order to avoid multi-definition */
extern struct Animals Ani;
extern struct Histobuckets Hb;
                /* 在 csvpackage.c 中 */
#include "csvpackage.h"

// Define the Ani and Hb structure
struct Animals Ani;
struct Histobuckets Hb;
                /* 在 testraw.c 中 */
```

```
38 #include "csvpackage.h"
```

再次运行 make 命令:

```
erwinzhou@erwinzhou-virtual-machine:~/lab/labcodes/DataSecurity/Lab05/experiment1$ make
gcc -I./include -c csvpackage.c
gcc -I./include -c testraw.c
gcc csvpackage.o laplace.o testraw.o -o testraw  -lm
gcc -I./include -c testhist.c
gcc csvpackage.o laplace.o testhist.o -o testhist -lm
erwinzhou@erwinzhou-virtual-machine:~/lab/labcodes/DataSecurity/Lab05/experiment1$
```

图 7: make 编译成功

如图7所示，可以看到**编译成功，便解决了问题。现在开始正式进行实验。**

五、 实验过程

编译完成后的可执行文件分为两个:

- `testraw`: **数据集直接加噪实验**，提供了数据集读取，给定隐私预算的噪音生成和加噪后结果展示的功能。
- `testhist`：**数据集直方图发布加噪实验**，提供了数据集读取，给定隐私预算的噪音生成和加噪后统计值输出的功能。

后面会依次运行两个不同的程序，

(一) 单独发布 `testraw`

1. 运行程序

首先直接运行 `testraw` 可执行程序，在数据集上直接进行加噪实验。**其默认指定隐私预算为 10 和 0.1，支持查询次数为 20 次**。运行结果如下图所示:

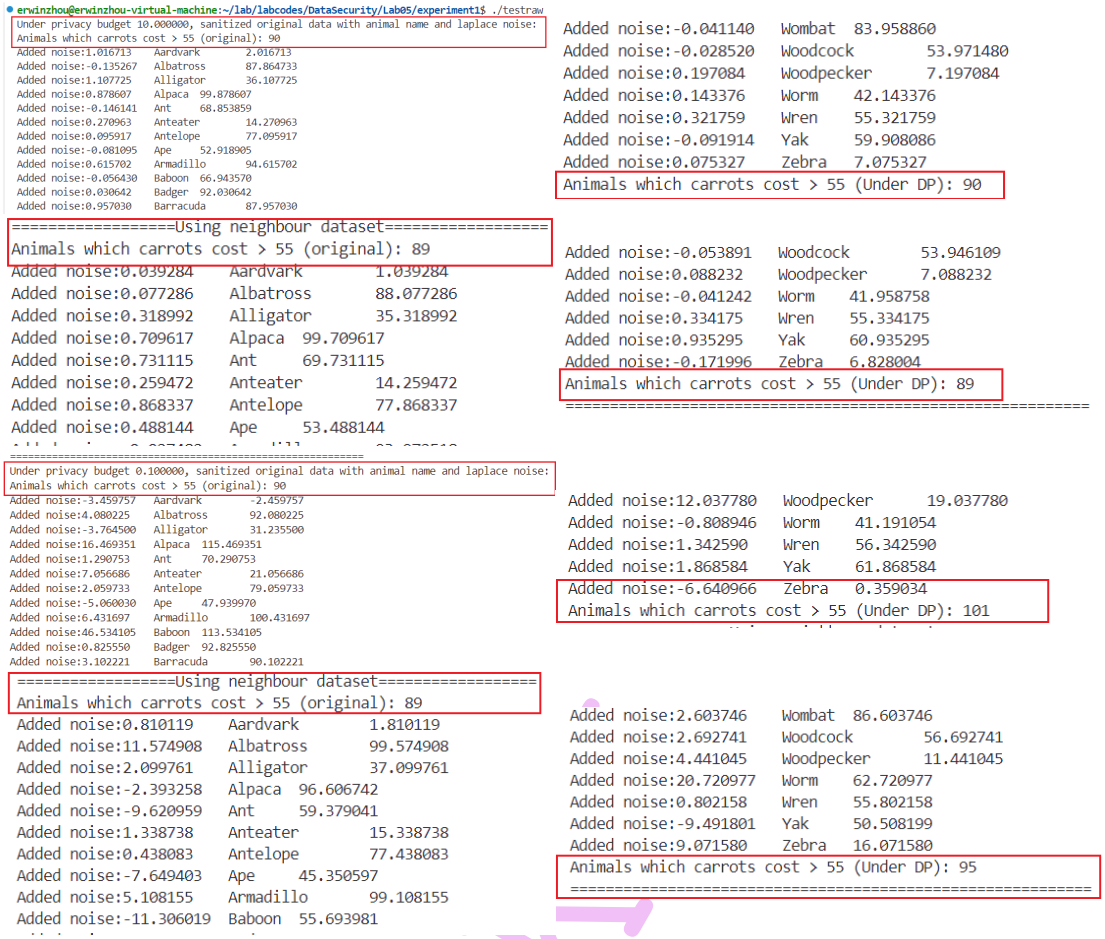

图 8: testraw 运行结果

2. 结果分析

如图8所示，接下来将会对该图中的结果分为四组，进行依次分析，**主要是对 DP 发布后的结果进行评估，说明隐私保护的效果，衡量其数据可用性与隐私保护效果。**

1. **第一组：隐私预算 = 10.0，不使用邻居数据集**

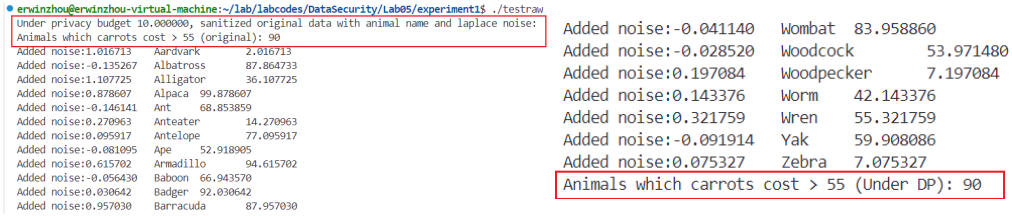

图 9: 第一组：隐私预算 = 10.0，不使用邻居数据集

```
1 Under privacy budget 10.000000, sanitized original data with animal name
  ↪  and laplace noise:
2 Animals which carrots cost > 55 (original): 90
3 Added noise:1.016713    Aardvark        2.016713
4 Added noise:-0.135267   Albatross       87.864733
```

```
Added noise:1.107725    Alligator       36.107725
/ * blablabla */
Added noise:0.143376    Worm    42.143376
Added noise:0.321759    Wren    55.321759
Added noise:-0.091914   Yak     59.908086
Added noise:0.075327    Zebra   7.075327
Animals which carrots cost > 55 (Under DP): 90
```

如图9所示，可以看到在隐私预算固定为 10.0，并且不使用邻居数据集而是保持原有数据集时。即**投入的隐私预算较大时，添加的噪声均位于 $-1 \leq noise \leq 1$ 区间之内**。

并且对于特定查询“每日进食大于 55 根胡萝卜的动物个数”都为 90，因此在该预算下，**加噪前和加噪后的响应一致，数据可用性好**。

2. **第二组：隐私预算 = 10.0，使用邻居数据集**

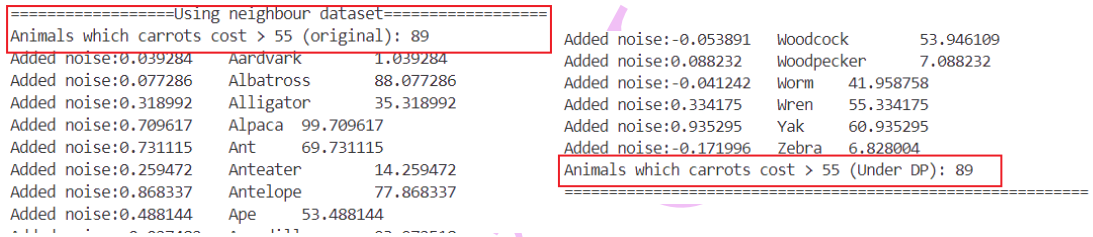

图 10: 第二组：隐私预算 = 10.0，使用邻居数据集

```
==========Using neighbour dataset==========
Animals which carrots cost > 55 (original): 89
Added noise:0.039284    Aardvark        1.039284
Added noise:0.077286    Albatross       88.077286
Added noise:0.318992    Alligator       35.318992
/ * blablabla */
Added noise:0.334175    Wren    55.334175
Added noise:0.935295    Yak     60.935295
Added noise:-0.171996   Zebra   6.828004
Animals which carrots cost > 55 (Under DP): 89
```

如图10所示，我们继续考察了**隐私预算设为 10.0 即仍然较高，并使用邻居数据集进行差分隐私处理的结果**。

使用邻居数据集，我们对每个动物的胡萝卜消费量加入了拉普拉斯噪声，隐私预算设置为 10.0。

如输出所示，在隐私预算为 10.0 的高设置下，加入的拉普拉斯噪声相对较小。结果表明，即使在添加了噪声之后，查询“每日进食大于 55 根胡萝卜的动物个数”的响应仍然为 89，显示了在较高的隐私预算下，数据的可用性得到了很好的保持。这证实了在较大的隐私预算下，**噪声的影响较小，数据的准确性和可用性较高**。

但是从另一方面思考**隐私保护的效果**。加噪后数据集对该查询的响应仍与数据集的变化一致，均为 89，体现出了 Dugeng 离开数据集造成的差异，**不能有效抵御对该查询的差分攻击。说明在隐私预算较高时候，隐私保护效果较差**。

3. **第三组：隐私预算 = 0.10，不使用邻居数据集**

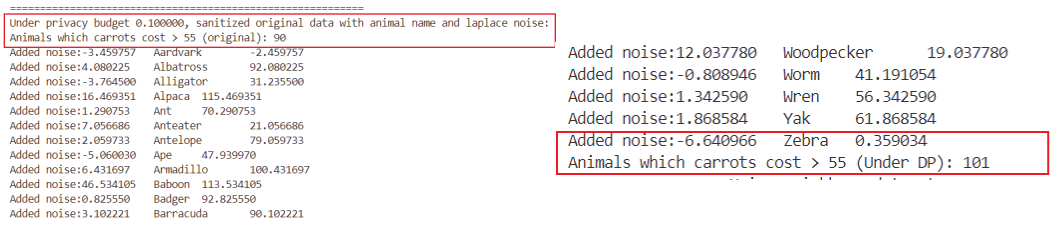

图 11: 第三组：隐私预算 = 0.10，不使用邻居数据集

```
1  ============================================================
2  Under privacy budget 0.100000, sanitized original data with animal name
   ↪  and laplace noise:
3  Animals which carrots cost > 55 (original): 90
4  Added noise:-3.459757   Aardvark        -2.459757
5  Added noise:4.080225    Albatross       92.080225
6  Added noise:-3.764500   Alligator       31.235500
7  / * blablabla */
8  Added noise:1.342590    Wren    56.342590
9  Added noise:1.868584    Yak     61.868584
10 Added noise:-6.640966   Zebra   0.359034
11 Animals which carrots cost > 55 (Under DP): 101
```


如图11所示，我们继续考察了**隐私预算设为 0.10，即非常低，并且不使用邻居数据集进行差分隐私处理的结果**。

如输出所示，在隐私预算为 0.10 的低设置下，加入的拉普拉斯噪声相对较大。结果表明，即使在添加了显著噪声之后，查询“每日进食大于 55 根胡萝卜的动物个数”的响应从 90 增加到了 101，显示了在较低的隐私预算下，数据的准确性受到了显著影响。这证实了在较小的隐私预算下，**噪声的影响较大，数据的准确性和可用性较低**。

4. **第四组：**隐私预算 = 0.10，使用邻居数据集

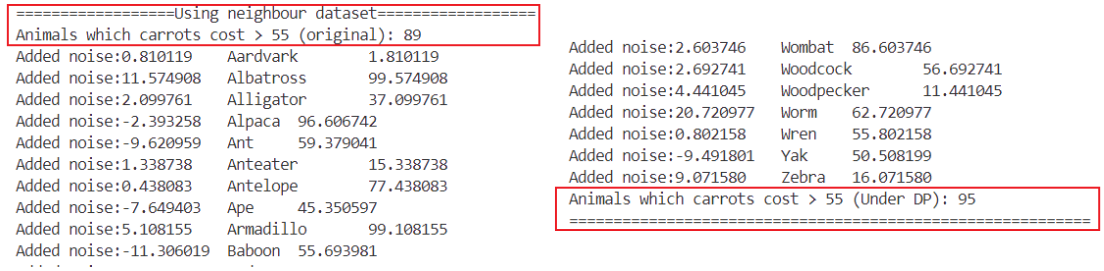

图 12: 第四组：隐私预算 = 0.10，使用邻居数据集

```
==================Using neighbour dataset==================
Animals which carrots cost > 55 (original): 89
Added noise:0.810119    Aardvark        1.810119
Added noise:11.574908   Albatross       99.574908
Added noise:2.099761    Alligator       37.099761
/ * blablabla */
Added noise:0.802158    Wren    55.802158
Added noise:-9.491801   Yak     50.508199
Added noise:9.071580    Zebra   16.071580
Animals which carrots cost > 55 (Under DP): 95
============================================================
```

如图12所示，我们继续考察了**隐私预算设为 0.10，这次使用邻居数据集进行差分隐私处理的结果**。

如输出所示，在隐私预算为 0.10 的低设置下，通过使用邻居数据集对数据进行加噪，我们观察到了一些重要的现象。虽然原始数据集中去除“Dugeng”项后直接影响了查询结果，但在加入拉普拉斯噪声后，加噪的结果显著变化，不再直接反映出“Dugeng”项的移除影响。**这种显著变化说明，低隐私预算的设置虽然减少了数据的直接可用性，但增强了数据在隐私保护方面的表现**。

这种现象揭示了在隐私预算较低时，尽管数据的可用性降低，差分隐私的实施却能有效抵御针对特定数据项的差分攻击。值得注意的是，由于差分隐私算法固有的随机性，以及本实验中算法的简单性，这种保护效果可能不总是一致。实验结果在不同的运行中可能有所变化，因此，可能需要多次执行实验来获取稳定和可靠的结果。

总体而言，这一发现强调了在设计隐私保护措施时考虑隐私预算和数据处理策略的重要性。**选择合适的隐私预算和数据集处理策略，可以在保护个人隐私和保持数据可用性之间找到更好的平衡点**。

(二) 直方图发布 `testhist`

1. 运行程序

然后运行 `testhist` 可执行程序，**数据集直方图发布加噪**。在该发布方式下，加噪的对象不再是数据本身，而是对数据进行分桶统计后的计数值进行加噪。**其默认指定隐私预算为 10 和 0.1，支持查询次数为 20 次**。运行结果如下图所示:

```
erwinzhou@erwinzhou-virtual-machine:~/lab/labcodes/DataSecurity/Lab05/experiment1$ ./testhist
Under privacy budget 10.000000, sanitized original bucket with laplace noise:
Added noise:0.049987    20-30   405.049987
Added noise:0.070591    30-40   436.070591
Added noise:-0.252260   40-50   420.747740
Added noise:-0.184343   50-60   456.815657
Added noise:0.265684    60-70   463.265684
==================Using neighbour dataset==================
Added noise:0.354999    20-30   405.354999
Added noise:0.917567    30-40   435.917567
Added noise:0.553866    40-50   421.553866
Added noise:0.069505    50-60   457.069505
Added noise:0.850041    60-70   463.850041
============================================================
Under privacy budget 0.100000, sanitized original bucket with laplace noise:
Added noise:3.934012    20-30   408.934012
Added noise:-2.139818   30-40   433.860182
Added noise:-6.059983   40-50   414.940017
Added noise:-0.321125   50-60   456.678875
Added noise:2.618170    60-70   465.618170
==================Using neighbour dataset==================
Added noise:2.978226    20-30   407.978226
Added noise:-0.050931   30-40   434.949069
Added noise:2.621044    40-50   423.621044
Added noise:3.562499    50-60   460.562499
Added noise:1.238240    60-70   464.238240
============================================================
```

图 13: testhist 运行结果

2. 结果分析

a) **第一组：使用隐私预算为 10.0**

```
Under privacy budget 10.000000, sanitized original bucket with laplace noise:
Added noise:0.049987    20-30   405.049987
Added noise:0.070591    30-40   436.070591
Added noise:-0.252260   40-50   420.747740
Added noise:-0.184343   50-60   456.815657
Added noise:0.265684    60-70   463.265684
==================Using neighbour dataset==================
Added noise:0.354999    20-30   405.354999
Added noise:0.917567    30-40   435.917567
Added noise:0.553866    40-50   421.553866
Added noise:0.069505    50-60   457.069505
Added noise:0.850041    60-70   463.850041
============================================================
```

- **噪音的影响**：从结果可以看出，大部分的分区中加噪后的计数值与原始值保持一致。仅在 40 分区和 60 分区的列中观察到细微的变化，分别增加了 1。这表明噪音的引入对**数据的整体影响较小，保持了较高的数据可用性**。
- **数据可用性**：尽管加入了噪音，但在大多数情况下，加噪后的数据与原始数据保持高

度一致。这说明使用的加噪技术在保护隐私的同时，**能够有效地保持数据的可用性**，这对于数据分析和决策制定来说至关重要。

- **隐私保护效果**：加噪过程显著增强了数据的隐私性。通过调整隐私预算和支持的查询次数，可以在隐私保护和数据可用性之间找到合适的平衡点。在此案例中，在 40 分区和 60 分区的列中观察到细微的变化，分别增加了 1。**因此相邻数据集的变化仍能被体现，隐私保护性并不是很优异**。隐私预算被设置为相对较高的值（10），这可能解释了为何数据变化不大，因此在实际应用中可能需要对隐私预算进行更细致的调整。

使用预算为 10 的差分隐私算法生成的数据和直方图如下：

分区	原始	加噪	加噪 + 相邻
20	405	405	405
30	436	436	436
40	421	421	422
50	457	457	457
60	463	463	464

表 2: 隐私预算 = 10.000000

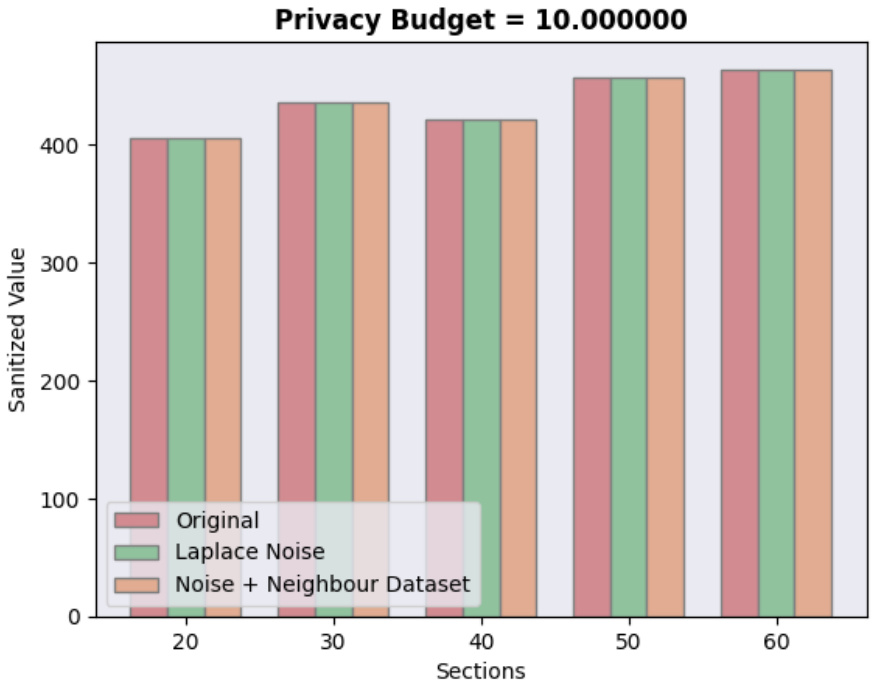

图 14: 隐私预算 = 10.000000 柱状图隐私保护效果展示

从表2和图14中可以看到，尽管加入了噪音，大部分数据在更大的尺度上观察时仍然保持着高度一致，这证明了较高的隐私预算情况下的优秀数据可用性。

b) **第二组：使用隐私预算为 0.10**

[1] ==========

```
Under privacy budget 0.100000, sanitized original bucket with laplace noise:
Added noise:3.934012    20-30   408.934012
Added noise:-2.139818   30-40   433.860182
Added noise:-6.059983   40-50   414.940017
Added noise:-0.321125   50-60   456.678875
Added noise:2.618170    60-70   465.618170
==================Using neighbour dataset==================
Added noise:2.978226    20-30   407.978226
Added noise:-0.050931   30-40   434.949069
Added noise:2.621044    40-50   423.621044
Added noise:3.562499    50-60   460.562499
Added noise:1.238240    60-70   464.238240
============================================================
```

- **噪音的影响**：根据所提供的数据，我们可以看出加噪后的数据在大部分分区与原始数据相近，但也存在一些变化。例如，在 40 分区，加噪数据从 421 降到 415，然后加噪 + 相邻为 424，显示出了较明显的波动。此外，50 分区和 60 分区的加噪 + 相邻数据也有所增加。这些变化表明，在隐私预算为 0.1 的较低设置下，**噪音对数据的影响略大于较高预算设置**。
- **数据可用性**：客观来讲可以看到数据出现了相较于 10.0 时更明显的波动，加噪后的数据与原始数据不再保持高度一致。这说明**在较低的隐私预算下，数据可用性稍有降低**。
- **隐私保护效果**：加噪增强了数据的隐私性，较低的隐私预算导致某些分区显示出较大的数据波动，特别是在 40 分区和 60 分区，相邻数据集的变化加入后，查询结果不减反增。**即虽然数据可用性变差，但能保护实际数据的变化不被攻击者获取，可抵御差分攻击**。

分区	原始	加噪	加噪 + 相邻
20	405	409	408
30	436	434	435
40	421	415	424
50	457	457	461
60	463	466	464

表 3: 隐私预算 = 0.100000

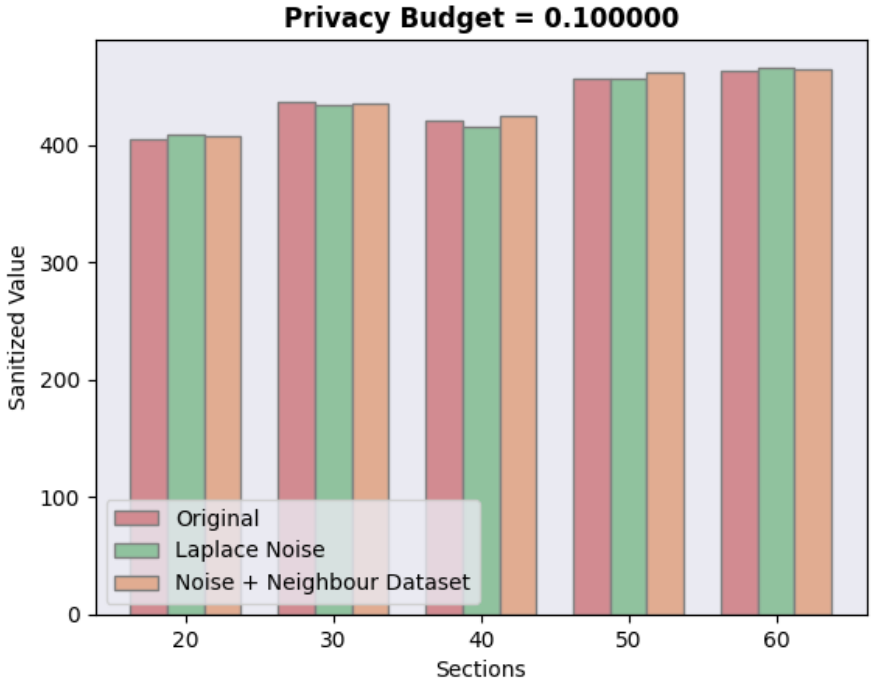

图 15: 隐私预算 = 0.100000 柱状图隐私保护效果展示

从表3和图15中可以看到，尽管加入了噪音，大部分数据的变化幅度仍然控制在较小范围内，说明加噪技术在保护隐私的同时，也能一定程度上保持数据的可用性。隐私保护效果此时也是很好的。

总的来说，隐私预算为 0.1 的加噪方法在保护隐私方面表现良好，但与较高隐私预算的情况相比，其和维持数据可用性略有不足。**在实际应用中，可能需要对隐私预算进行更细致的调整，以达到更优的隐私保护和数据可用性的平衡**。

(三) Trade-off Discussion

在差分隐私领域，拉普拉斯机制是一种常用的方法，通过在数据查询结果中加入拉普拉斯噪音来保护隐私。然而，噪音的引入同时影响了数据的可用性。**从上面的结果中我们可以发现数据的可用性和隐私保护效果之间存在着微妙的平衡需要我们进行探索**。

首先，隐私预算（ϵ）的选择对于权衡具有决定性影响。较低的 ϵ 值意味着较高的隐私保护（比如我们实验中设置的 `0.10`），但同时也会导致更大的噪音量，从而降低数据的可用性。相反，较高的 ϵ 值虽然能提高数据的准确性（比如我们实验中设置的 `10.0`），但却减弱了隐私保护。因此，合理选择 ϵ 值是实现数据可用性与隐私保护平衡的关键。

其次，**可以采用分层或分区的方法来局部优化噪音的分布**。例如，对于数据集中不同的敏感度区域，可以根据其敏感性调整不同的 ϵ 分配。这种策略允许对较不敏感的数据施加较少的噪音，而对高度敏感的数据施加更多的噪音，从而在不牺牲整体数据可用性的情况下，增强隐私保护。

再者，**引入隐私保护的算法优化也是一种方法**。本次案例是某动物园和医疗数据，实际上可以针对特殊的场景开发更高效的差分隐私算法，以减少在保持相同隐私级别的条件下所需的噪音量。例如，通过改进数据的聚合和抽样方法，可以在减少噪音的同时，保持数据的统计意义和可用性。

最后，**用户查询行为的管理也是实现权衡的一种方法**。系统可以限制频繁的或高敏感性的查询，或者在查询之间设定时间间隔，以控制隐私预算的消耗速度，这有助于在长期内保持较好的

数据可用性和隐私保护。

通过上述方法，我们可以在交互式发布方式中更好地实现数据可用性和隐私保护的平衡。**到此我们本次实验全部结束，总体来说实验较为成功**。

六、 实验总结与思考

本次实验我通过将课堂上老师讲授的差分隐私和交互式发布的数据安全知识在课后进一步进行了复习，其中差分隐私的相关数学理论推导十分有趣令我印象深刻，如何在保证数据可用性的的基础上提高对个体隐私的保护。跟着参考资料和老师讲解视频的思路，对参考代码进行了研读。

由此**我基于教材中的例子，完成了本次的实验内容**。工作包括：

1. 熟悉了 Linux 环境中进行解压和编译的方式；
2. 通过实践，了解了如何对**差分隐私的交互式发布方案进行 DP 方案设计**；
3. 基于参考代码，**完成了对应的实验练习，解决了遇到的问题和困难。让我对差分隐私的原理理解更加深刻**；
4. 基于实验得出的**差分隐私结果进行了详尽的评估，并对隐私保护的效果进行了详尽的分析。主要针对于数据可用性和隐私保护两个方面，并通过图表进行了更好的可视化的展示。**
5. 最后我还拓展性地探索了在数据可用性和隐私保护效果之间的 `Trade-off` 的方式，进行了初步的设想和讨论。加深了对隐私保护相关理论知识和研究成果的实践性理解与认知。

总的来说，本次实验我收获颇丰，希望在后面的实验中继续努力，将数据安全领域的知识熟记于心，并在实验中反复巩固，不断探索。

七、 附录

(一) 单独发布 `testraw` 运行结果

```
erwinzhou@erwinzhou-virtual-machine:~/lab/labcodes/DataSecurity/Lab05/experiment1$ ./testraw
Under privacy budget 10.000000, sanitized original data with animal name and laplace noise:
Animals which carrots cost > 55 (original): 90
Added noise:1.016713    Aardvark        2.016713
Added noise:-0.135267   Albatross       87.864733
Added noise:1.107725    Alligator       36.107725
Added noise:0.878607    Alpaca  99.878607
Added noise:-0.146141   Ant     68.853859
Added noise:0.270963    Anteater        14.270963
Added noise:0.095917    Antelope        77.095917
Added noise:-0.081095   Ape     52.918905
Added noise:0.615702    Armadillo       94.615702
Added noise:-0.056430   Baboon  66.943570
```

```
Added noise:0.030642    Badger  92.030642
Added noise:0.957030    Barracuda       87.957030
Added noise:0.028449    Bat     70.028449
Added noise:-0.007833   Bear    30.992167
Added noise:0.060355    Beaver  14.060355
Added noise:0.425823    Bee     14.425823
Added noise:-0.294194   Bison   60.705806
Added noise:-0.014838   Boar    56.985162
Added noise:-0.132315   Buffalo 67.867685
Added noise:0.770278    Butterfly       13.770278
Added noise:0.743697    Camel   21.743697
Added noise:0.196318    Caribou 38.196318
Added noise:-0.400176   Cat     91.599824
Added noise:0.020877    Caterpillar     39.020877
Added noise:-0.003236   Cattle  45.996764
Added noise:0.036699    Chamois 36.036699
Added noise:0.584168    Cheetah 23.584168
Added noise:-0.005605   Chicken 75.994395
Added noise:0.722879    Chimpanzee      8.722879
Added noise:0.076734    Chinchilla      69.076734
Added noise:-0.113659   Chough  34.886341
Added noise:0.017644    Clam    83.017644
Added noise:-0.015638   Capybara        39.984362
Added noise:-0.016345   Cobra   73.983655
Added noise:0.967674    Cockroach       17.967674
Added noise:-0.008716   Cod     76.991284
Added noise:-0.144577   Cormorant       51.855423
Added noise:0.033709    Coyote  31.033709
Added noise:0.324307    Crab    14.324307
Added noise:-0.099927   Crane   39.900073
Added noise:0.056502    Crocodile       46.056502
Added noise:-0.072086   Crow    98.927914
Added noise:0.348502    Curlew  44.348502
Added noise:0.084673    Deer    15.084673
Added noise:-0.109929   Dinosaur        88.890071
Added noise:0.879530    Dog     36.879530
Added noise:-0.352120   Dogfish 97.647880
Added noise:0.011012    Dolphin 20.011012
Added noise:-0.080667   Donkey  55.919333
Added noise:0.988619    Dove    90.988619
Added noise:0.876940    Dragonfly       5.876940
Added noise:-0.200316   Duck    74.799684
Added noise:-0.247020   Dugong  55.752980
Added noise:0.123190    Eagle   23.123190
```

```
Added noise:0.417415    Echidna 49.417415
Added noise:0.008237    Eel     83.008237
Added noise:0.960952    Elephant        55.960952
Added noise:0.024466    Elk     22.024466
Added noise:0.058831    Emu     7.058831
Added noise:0.260028    Falcon  16.260028
Added noise:0.045368    Ferret  91.045368
Added noise:0.547617    Finch   80.547617
Added noise:0.807835    Fish    21.807835
Added noise:0.001032    Flamingo        56.001032
Added noise:-0.035665   Fly     9.964335
Added noise:-0.036765   Fox     27.963235
Added noise:-0.323215   Frog    28.676785
Added noise:0.189394    Gazelle 19.189394
Added noise:1.161872    Gerbil  74.161872
Added noise:0.012372    Giraffe 45.012372
Added noise:0.403070    Gnat    5.403070
Added noise:-0.008970   Goat    19.991030
Added noise:-0.062030   Goldfinch       27.937970
Added noise:-0.536951   Goldfish        44.463049
Added noise:0.005212    Goose   39.005212
Added noise:0.537896    Gorilla 64.537896
Added noise:0.861832    Grasshopper     22.861832
Added noise:0.202825    Gull    7.202825
Added noise:-0.066313   Hamster 29.933687
Added noise:-0.274587   Hare    9.725413
Added noise:0.179130    Hawk    48.179130
Added noise:-0.085323   Hedgehog        59.914677
Added noise:0.024743    Heron   73.024743
Added noise:0.108650    Herring 82.108650
Added noise:0.073511    Hippopotamus    96.073511
Added noise:0.250761    Hornet  82.250761
Added noise:0.626034    Horse   38.626034
Added noise:-0.004141   Hummingbird     83.995859
Added noise:0.656517    Hyena   39.656517
Added noise:0.950842    Jackal  12.950842
Added noise:-0.096623   Jaguar  74.903377
Added noise:0.440222    Jay     75.440222
Added noise:0.045891    Kangaroo        45.045891
Added noise:0.059707    Koala   87.059707
Added noise:0.551478    Lark    91.551478
Added noise:0.510020    Lemur   33.510020
Added noise:0.363030    Leopard 40.363030
Added noise:0.407753    Lion    0.407753
```

```
Added noise:-0.029091   Llama    66.970909
Added noise:0.336051    Lobster  63.336051
Added noise:0.196842    Locust   16.196842
Added noise:0.911062    Mallard  93.911062
Added noise:0.007212    Manatee  19.007212
Added noise:-0.012964   Marten   71.987036
Added noise:0.102521    Meerkat  46.102521
Added noise:0.818453    Mole     73.818453
Added noise:-0.036824   Monkey   97.963176
Added noise:-0.046658   Moose    85.953342
Added noise:0.447436    Mosquito         3.447436
Added noise:0.743221    Mouse    64.743221
Added noise:-0.120911   Mule     93.879089
Added noise:0.163391    Narwhal  75.163391
Added noise:0.955839    Newt     2.955839
Added noise:-0.051674   Nightingale      86.948326
Added noise:0.014901    Octopus  74.014901
Added noise:0.544571    Opossum  79.544571
Added noise:0.892270    Ostrich  56.892270
Added noise:0.002263    Otter    51.002263
Added noise:0.683725    Owl      77.683725
Added noise:0.079551    Ox       81.079551
Added noise:0.067598    Oyster   42.067598
Added noise:0.000297    Panther  90.000297
Added noise:1.147798    Parrot   97.147798
Added noise:1.418793    Peafowl  5.418793
Added noise:-0.123148   Pelican  57.876852
Added noise:-0.063132   Penguin  72.936868
Added noise:-0.027826   Pheasant         26.972174
Added noise:0.804218    Pig      56.804218
Added noise:0.046713    Pigeon   80.046713
Added noise:0.041793    Porcupine        10.041793
Added noise:0.479372    Porpoise         35.479372
Added noise:-0.193808   Quail    85.806192
Added noise:0.658148    Rabbit   100.658148
Added noise:0.459811    Raccoon  16.459811
Added noise:0.548264    Rail     7.548264
Added noise:-0.023373   Ram      29.976627
Added noise:0.017360    Rat      84.017360
Added noise:0.792811    Raven    50.792811
Added noise:-0.089127   Rhinoceros       85.910873
Added noise:0.048049    Salamander       21.048049
Added noise:-0.022207   Salmon   14.977793
Added noise:-0.069720   Sardine  65.930280
```

```
Added noise:0.642875    Scorpion        75.642875
Added noise:0.067606    Seahorse        71.067606
Added noise:-0.009111   Seal    55.990889
Added noise:-0.080107   Shark   51.919893
Added noise:-0.003474   Sheep   98.996526
Added noise:0.146109    Shrew   45.146109
Added noise:1.300122    Shrimp  85.300122
Added noise:-0.013493   Skunk   98.986507
Added noise:0.038047    Snail   51.038047
Added noise:0.424703    Snake   37.424703
Added noise:0.059485    Spider  96.059485
Added noise:0.409668    Squid   90.409668
Added noise:1.050605    Squirrel        93.050605
Added noise:1.224208    Starling        81.224208
Added noise:0.648517    Stingray        96.648517
Added noise:0.034712    Stinkbug        31.034712
Added noise:1.000800    Stork   40.000800
Added noise:-0.076672   Swallow 1.923328
Added noise:0.027260    Swan    68.027260
Added noise:0.465866    Tapir   53.465866
Added noise:0.141144    Tiger   47.141144
Added noise:-0.225929   Toad    81.774071
Added noise:-0.004569   Trout   50.995431
Added noise:0.279483    Turkey  57.279483
Added noise:0.605570    Turtle  10.605570
Added noise:0.476256    Viper   28.476256
Added noise:0.002861    Vulture 91.002861
Added noise:-0.200819   Walrus  93.799181
Added noise:-0.045307   Wasp    50.954693
Added noise:-0.079803   Weasel  19.920197
Added noise:0.720192    Whale   87.720192
Added noise:1.160094    Wolf    82.160094
Added noise:0.944492    Wolverine       36.944492
Added noise:-0.041140   Wombat  83.958860
Added noise:-0.028520   Woodcock        53.971480
Added noise:0.197084    Woodpecker      7.197084
Added noise:0.143376    Worm    42.143376
Added noise:0.321759    Wren    55.321759
Added noise:-0.091914   Yak     59.908086
Added noise:0.075327    Zebra   7.075327
Animals which carrots cost > 55 (Under DP): 90
==================Using neighbour dataset==================
Animals which carrots cost > 55 (original): 89
Added noise:0.039284    Aardvark        1.039284
```

```
Added noise:0.077286    Albatross       88.077286
Added noise:0.318992    Alligator       35.318992
Added noise:0.709617    Alpaca  99.709617
Added noise:0.731115    Ant     69.731115
Added noise:0.259472    Anteater        14.259472
Added noise:0.868337    Antelope        77.868337
Added noise:0.488144    Ape     53.488144
Added noise:-0.027482   Armadillo       93.972518
Added noise:0.349344    Baboon  67.349344
Added noise:-0.089117   Badger  91.910883
Added noise:0.166911    Barracuda       87.166911
Added noise:0.392170    Bat     70.392170
Added noise:0.635273    Bear    31.635273
Added noise:-0.010526   Beaver  13.989474
Added noise:0.538829    Bee     14.538829
Added noise:0.514136    Bison   61.514136
Added noise:-0.138970   Boar    56.861030
Added noise:0.331654    Buffalo 68.331654
Added noise:0.607555    Butterfly       13.607555
Added noise:0.887734    Camel   21.887734
Added noise:-0.113797   Caribou 37.886203
Added noise:0.654436    Cat     92.654436
Added noise:1.023214    Caterpillar     40.023214
Added noise:0.733536    Cattle  46.733536
Added noise:0.000558    Chamois 36.000558
Added noise:-0.006557   Cheetah 22.993443
Added noise:0.075431    Chicken 76.075431
Added noise:0.698282    Chimpanzee      8.698282
Added noise:0.469975    Chinchilla      69.469975
Added noise:0.457709    Chough  35.457709
Added noise:0.569067    Clam    83.569067
Added noise:0.376128    Capybara        40.376128
Added noise:0.014425    Cobra   74.014425
Added noise:-0.020974   Cockroach       16.979026
Added noise:0.113849    Cod     77.113849
Added noise:-0.030781   Cormorant       51.969219
Added noise:0.044193    Coyote  31.044193
Added noise:0.334392    Crab    14.334392
Added noise:0.041592    Crane   40.041592
Added noise:0.942418    Crocodile       46.942418
Added noise:0.803417    Crow    99.803417
Added noise:0.077310    Curlew  44.077310
Added noise:0.163740    Deer    15.163740
Added noise:0.695127    Dinosaur        89.695127
```

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Added noise:0.052075    Dog      36.052075
Added noise:-0.178653   Dogfish 97.821347
Added noise:-0.127207   Dolphin 19.872793
Added noise:0.908405    Donkey   56.908405
Added noise:0.439782    Dove     90.439782
Added noise:0.914681    Dragonfly        5.914681
Added noise:0.864983    Duck     75.864983
Added noise:0.856807    Eagle    23.856807
Added noise:-0.048076   Echidna 48.951924
Added noise:0.015151    Eel      83.015151
Added noise:0.053992    Elephant         55.053992
Added noise:-0.029473   Elk      21.970527
Added noise:1.003993    Emu      8.003993
Added noise:0.228104    Falcon   16.228104
Added noise:-0.118236   Ferret   90.881764
Added noise:1.024865    Finch    81.024865
Added noise:0.066381    Fish     21.066381
Added noise:0.893593    Flamingo         56.893593
Added noise:-0.119169   Fly      9.880831
Added noise:0.014490    Fox      28.014490
Added noise:0.683423    Frog     29.683423
Added noise:0.016816    Gazelle 19.016816
Added noise:0.218028    Gerbil   73.218028
Added noise:0.845456    Giraffe 45.845456
Added noise:0.669796    Gnat     5.669796
Added noise:0.937912    Goat     20.937912
Added noise:0.096481    Goldfinch        28.096481
Added noise:-0.054047   Goldfish         44.945953
Added noise:0.418131    Goose    39.418131
Added noise:-0.000107   Gorilla 63.999893
Added noise:-0.273250   Grasshopper      21.726750
Added noise:0.041385    Gull     7.041385
Added noise:0.084890    Hamster 30.084890
Added noise:0.067022    Hare     10.067022
Added noise:1.311033    Hawk     49.311033
Added noise:-0.044567   Hedgehog         59.955433
Added noise:0.706088    Heron    73.706088
Added noise:0.886182    Herring 82.886182
Added noise:0.860533    Hippopotamus     96.860533
Added noise:0.885250    Hornet   82.885250
Added noise:-0.134270   Horse    37.865730
Added noise:0.046283    Hummingbird      84.046283
Added noise:0.569038    Hyena    39.569038
Added noise:-0.097721   Jackal   11.902279
```

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278 Added noise:-0.046572   Jaguar  74.953428
279 Added noise:0.698503    Jay     75.698503
280 Added noise:0.347924    Kangaroo        45.347924
281 Added noise:0.392936    Koala   87.392936
282 Added noise:0.004198    Lark    91.004198
283 Added noise:-0.071046   Lemur   32.928954
284 Added noise:-0.042804   Leopard 39.957196
285 Added noise:0.251736    Lion    0.251736
286 Added noise:0.801719    Llama   67.801719
287 Added noise:0.121757    Lobster 63.121757
288 Added noise:1.064012    Locust  17.064012
289 Added noise:0.079311    Mallard 93.079311
290 Added noise:0.020812    Manatee 19.020812
291 Added noise:0.260563    Marten  72.260563
292 Added noise:0.630108    Meerkat 46.630108
293 Added noise:0.079391    Mole    73.079391
294 Added noise:0.499301    Monkey  98.499301
295 Added noise:0.038656    Moose   86.038656
296 Added noise:-0.028039   Mosquito        2.971961
297 Added noise:0.430664    Mouse   64.430664
298 Added noise:-0.080138   Mule    93.919862
299 Added noise:-0.000913   Narwhal 74.999087
300 Added noise:0.071259    Newt    2.071259
301 Added noise:-0.127016   Nightingale     86.872984
302 Added noise:0.007874    Octopus 74.007874
303 Added noise:0.015196    Opossum 79.015196
304 Added noise:-0.096639   Ostrich 55.903361
305 Added noise:0.990925    Otter   51.990925
306 Added noise:0.245685    Owl     77.245685
307 Added noise:-0.009929   Ox      80.990071
308 Added noise:0.036395    Oyster  42.036395
309 Added noise:0.073556    Panther 90.073556
310 Added noise:-0.359709   Parrot  95.640291
311 Added noise:0.004955    Peafowl 4.004955
312 Added noise:0.895825    Pelican 58.895825
313 Added noise:0.802344    Penguin 73.802344
314 Added noise:-0.087021   Pheasant        26.912979
315 Added noise:0.203684    Pig     56.203684
316 Added noise:-0.205320   Pigeon  79.794680
317 Added noise:-0.012813   Porcupine       9.987187
318 Added noise:0.943039    Porpoise        35.943039
319 Added noise:-0.043386   Quail   85.956614
320 Added noise:-0.062936   Rabbit  99.937064
321 Added noise:-0.028451   Raccoon 15.971549
```

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322 Added noise:0.476773    Rail     7.476773
323 Added noise:0.282763    Ram      30.282763
324 Added noise:-0.052752   Rat      83.947248
325 Added noise:-0.093263   Raven    49.906737
326 Added noise:0.742496    Rhinoceros       86.742496
327 Added noise:0.558689    Salamander       21.558689
328 Added noise:1.086547    Salmon   16.086547
329 Added noise:0.863105    Sardine  66.863105
330 Added noise:0.885113    Scorpion         75.885113
331 Added noise:0.042350    Seahorse         71.042350
332 Added noise:0.938089    Seal     56.938089
333 Added noise:0.349377    Shark    52.349377
334 Added noise:-0.236715   Sheep    98.763285
335 Added noise:0.600233    Shrew    45.600233
336 Added noise:0.567275    Shrimp   84.567275
337 Added noise:-0.425330   Skunk    98.574670
338 Added noise:0.500927    Snail    51.500927
339 Added noise:1.065138    Snake    38.065138
340 Added noise:1.049533    Spider   97.049533
341 Added noise:0.607456    Squid    90.607456
342 Added noise:-0.047400   Squirrel         91.952600
343 Added noise:-0.062158   Starling         79.937842
344 Added noise:0.214662    Stingray         96.214662
345 Added noise:0.253795    Stinkbug         31.253795
346 Added noise:0.464045    Stork    39.464045
347 Added noise:1.111802    Swallow  3.111802
348 Added noise:0.029866    Swan     68.029866
349 Added noise:0.021693    Tapir    53.021693
350 Added noise:-0.163303   Tiger    46.836697
351 Added noise:0.229457    Toad     82.229457
352 Added noise:0.471847    Trout    51.471847
353 Added noise:0.296379    Turkey   57.296379
354 Added noise:0.623426    Turtle   10.623426
355 Added noise:-0.184476   Viper    27.815524
356 Added noise:-0.007664   Vulture  90.992336
357 Added noise:0.061137    Walrus   94.061137
358 Added noise:-0.066961   Wasp     50.933039
359 Added noise:0.913956    Weasel   20.913956
360 Added noise:0.044482    Whale    87.044482
361 Added noise:0.339230    Wolf     81.339230
362 Added noise:-0.008575   Wolverine        35.991425
363 Added noise:0.820553    Wombat   84.820553
364 Added noise:-0.053891   Woodcock         53.946109
365 Added noise:0.088232    Woodpecker       7.088232
```

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Added noise:-0.041242   Worm    41.958758
Added noise:0.334175    Wren    55.334175
Added noise:0.935295    Yak     60.935295
Added noise:-0.171996   Zebra   6.828004
Animals which carrots cost > 55 (Under DP): 89
============================================================
Under privacy budget 0.100000, sanitized original data with animal name and laplace noise:
Animals which carrots cost > 55 (original): 90
Added noise:-3.459757   Aardvark       -2.459757
Added noise:4.080225    Albatross      92.080225
Added noise:-3.764500   Alligator      31.235500
Added noise:16.469351   Alpaca  115.469351
Added noise:1.290753    Ant     70.290753
Added noise:7.056686    Anteater       21.056686
Added noise:2.059733    Antelope       79.059733
Added noise:-5.060030   Ape     47.939970
Added noise:6.431697    Armadillo      100.431697
Added noise:46.534105   Baboon  113.534105
Added noise:0.825550    Badger  92.825550
Added noise:3.102221    Barracuda      90.102221
Added noise:2.924504    Bat     72.924504
Added noise:4.662599    Bear    35.662599
Added noise:3.844590    Beaver  17.844590
Added noise:13.934540   Bee     27.934540
Added noise:8.573358    Bison   69.573358
Added noise:6.207573    Boar    63.207573
Added noise:1.692254    Buffalo 69.692254
Added noise:2.859914    Butterfly      15.859914
Added noise:0.882496    Camel   21.882496
Added noise:20.503688   Caribou 58.503688
Added noise:7.541913    Cat     99.541913
Added noise:-26.023588  Caterpillar    12.976412
Added noise:13.625969   Cattle  59.625969
Added noise:8.388065    Chamois 44.388065
Added noise:3.158511    Cheetah 26.158511
Added noise:16.882320   Chicken 92.882320
Added noise:4.047010    Chimpanzee     12.047010
Added noise:6.804377    Chinchilla     75.804377
Added noise:0.140872    Chough  35.140872
Added noise:1.469650    Clam    84.469650
Added noise:5.316757    Capybara       45.316757
Added noise:-16.496362  Cobra   57.503638
Added noise:13.450798   Cockroach      30.450798
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Added noise:-2.755496   Cod      74.244504
Added noise:7.103444    Cormorant        59.103444
Added noise:-5.820951   Coyote   25.179049
Added noise:13.193622   Crab     27.193622
Added noise:5.532020    Crane    45.532020
Added noise:17.217973   Crocodile        63.217973
Added noise:1.330426    Crow     100.330426
Added noise:7.506556    Curlew   51.506556
Added noise:3.256048    Deer     18.256048
Added noise:7.077161    Dinosaur         96.077161
Added noise:-10.721947  Dog      25.278053
Added noise:6.831102    Dogfish  104.831102
Added noise:1.737732    Dolphin  21.737732
Added noise:6.915143    Donkey   62.915143
Added noise:-6.543995   Dove     83.456005
Added noise:7.132054    Dragonfly        12.132054
Added noise:3.087646    Duck     78.087646
Added noise:-51.542114  Dugong   4.457886
Added noise:-3.558536   Eagle    19.441464
Added noise:3.878835    Echidna  52.878835
Added noise:15.109665   Eel      98.109665
Added noise:4.753234    Elephant         59.753234
Added noise:7.712998    Elk      29.712998
Added noise:-1.494560   Emu      5.505440
Added noise:-6.484410   Falcon   9.515590
Added noise:1.330838    Ferret   92.330838
Added noise:-5.515957   Finch    74.484043
Added noise:-1.111778   Fish     19.888222
Added noise:2.446891    Flamingo         58.446891
Added noise:-7.526668   Fly      2.473332
Added noise:2.226070    Fox      30.226070
Added noise:5.399567    Frog     34.399567
Added noise:0.652356    Gazelle  19.652356
Added noise:0.898532    Gerbil   73.898532
Added noise:-8.642121   Giraffe  36.357879
Added noise:22.038521   Gnat     27.038521
Added noise:14.027314   Goat     34.027314
Added noise:4.505570    Goldfinch        32.505570
Added noise:27.488031   Goldfish         72.488031
Added noise:1.319835    Goose    40.319835
Added noise:-1.808360   Gorilla  62.191640
Added noise:6.403670    Grasshopper      28.403670
Added noise:-19.488608  Gull     -12.488608
Added noise:3.737979    Hamster  33.737979
```

```
Added noise:6.547578    Hare    16.547578
Added noise:-6.707890   Hawk    41.292110
Added noise:6.517922    Hedgehog        66.517922
Added noise:-7.827510   Heron   65.172490
Added noise:2.467149    Herring 84.467149
Added noise:1.337579    Hippopotamus    97.337579
Added noise:9.137333    Hornet  91.137333
Added noise:17.262857   Horse   55.262857
Added noise:17.757763   Hummingbird     101.757763
Added noise:3.483953    Hyena   42.483953
Added noise:4.689896    Jackal  16.689896
Added noise:-4.544601   Jaguar  70.455399
Added noise:2.423821    Jay     77.423821
Added noise:5.186024    Kangaroo        50.186024
Added noise:-5.074241   Koala   81.925759
Added noise:-5.025524   Lark    85.974476
Added noise:1.099050    Lemur   34.099050
Added noise:2.733098    Leopard 42.733098
Added noise:4.302360    Lion    4.302360
Added noise:9.655720    Llama   76.655720
Added noise:4.786262    Lobster 67.786262
Added noise:2.055742    Locust  18.055742
Added noise:0.266303    Mallard 93.266303
Added noise:10.049830   Manatee 29.049830
Added noise:2.543019    Marten  74.543019
Added noise:22.701034   Meerkat 68.701034
Added noise:-1.691497   Mole    71.308503
Added noise:2.547215    Monkey  100.547215
Added noise:3.998520    Moose   89.998520
Added noise:5.220939    Mosquito        8.220939
Added noise:-0.685725   Mouse   63.314275
Added noise:-2.985254   Mule    91.014746
Added noise:5.062473    Narwhal 80.062473
Added noise:2.471056    Newt    4.471056
Added noise:3.167165    Nightingale     90.167165
Added noise:30.778817   Octopus 104.778817
Added noise:-1.447357   Opossum 77.552643
Added noise:-8.169528   Ostrich 47.830472
Added noise:11.931376   Otter   62.931376
Added noise:-10.010795  Owl     66.989205
Added noise:-6.510306   Ox      74.489694
Added noise:19.106016   Oyster  61.106016
Added noise:1.835543    Panther 91.835543
Added noise:6.495438    Parrot  102.495438
```

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Added noise:27.408638   Peafowl 31.408638
Added noise:4.127769    Pelican 62.127769
Added noise:10.890976   Penguin 83.890976
Added noise:7.425442    Pheasant        34.425442
Added noise:-0.269001   Pig     55.730999
Added noise:1.739832    Pigeon  81.739832
Added noise:12.356631   Porcupine       22.356631
Added noise:0.482941    Porpoise        35.482941
Added noise:9.810967    Quail   95.810967
Added noise:5.771950    Rabbit  105.771950
Added noise:0.804248    Raccoon 16.804248
Added noise:0.290212    Rail    7.290212
Added noise:1.976471    Ram     31.976471
Added noise:8.503258    Rat     92.503258
Added noise:3.126003    Raven   53.126003
Added noise:26.380252   Rhinoceros      112.380252
Added noise:5.644117    Salamander      26.644117
Added noise:3.970904    Salmon  18.970904
Added noise:-5.210250   Sardine 60.789750
Added noise:11.789106   Scorpion        86.789106
Added noise:4.639524    Seahorse        75.639524
Added noise:15.915155   Seal    71.915155
Added noise:8.687250    Shark   60.687250
Added noise:-22.057411  Sheep   76.942589
Added noise:1.608358    Shrew   46.608358
Added noise:8.302436    Shrimp  92.302436
Added noise:5.331411    Skunk   104.331411
Added noise:0.010536    Snail   51.010536
Added noise:5.708263    Snake   42.708263
Added noise:-23.819125  Spider  72.180875
Added noise:0.965664    Squid   90.965664
Added noise:14.752744   Squirrel        106.752744
Added noise:0.104778    Starling        80.104778
Added noise:2.687087    Stingray        98.687087
Added noise:8.827836    Stinkbug        39.827836
Added noise:-7.934650   Stork   31.065350
Added noise:5.264052    Swallow 7.264052
Added noise:3.934027    Swan    71.934027
Added noise:23.128063   Tapir   76.128063
Added noise:20.535998   Tiger   67.535998
Added noise:26.706072   Toad    108.706072
Added noise:12.707171   Trout   63.707171
Added noise:9.068510    Turkey  66.068510
Added noise:23.935980   Turtle  33.935980
```

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Added noise:0.360669    Viper   28.360669
Added noise:-1.565590   Vulture 89.434410
Added noise:11.735634   Walrus  105.735634
Added noise:3.873402    Wasp    54.873402
Added noise:4.358664    Weasel  24.358664
Added noise:2.654266    Whale   89.654266
Added noise:-3.150090   Wolf    77.849910
Added noise:-8.759634   Wolverine       27.240366
Added noise:-20.635357  Wombat  63.364643
Added noise:-23.430604  Woodcock        30.569396
Added noise:12.037780   Woodpecker      19.037780
Added noise:-0.808946   Worm    41.191054
Added noise:1.342590    Wren    56.342590
Added noise:1.868584    Yak     61.868584
Added noise:-6.640966   Zebra   0.359034
Animals which carrots cost > 55 (Under DP): 101
==================Using neighbour dataset==================
Animals which carrots cost > 55 (original): 89
Added noise:0.810119    Aardvark        1.810119
Added noise:11.574908   Albatross       99.574908
Added noise:2.099761    Alligator       37.099761
Added noise:-2.393258   Alpaca  96.606742
Added noise:-9.620959   Ant     59.379041
Added noise:1.338738    Anteater        15.338738
Added noise:0.438083    Antelope        77.438083
Added noise:-7.649403   Ape     45.350597
Added noise:5.108155    Armadillo       99.108155
Added noise:-11.306019  Baboon  55.693981
Added noise:63.004636   Badger  155.004636
Added noise:0.017274    Barracuda       87.017274
Added noise:19.582878   Bat     89.582878
Added noise:12.854026   Bear    43.854026
Added noise:9.626097    Beaver  23.626097
Added noise:4.462186    Bee     18.462186
Added noise:0.546758    Bison   61.546758
Added noise:5.095165    Boar    62.095165
Added noise:3.826214    Buffalo 71.826214
Added noise:2.269427    Butterfly       15.269427
Added noise:2.837108    Camel   23.837108
Added noise:-0.395877   Caribou 37.604123
Added noise:-1.102906   Cat     90.897094
Added noise:1.945713    Caterpillar     40.945713
Added noise:-35.490874  Cattle  10.509126
Added noise:5.473473    Chamois 41.473473
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585 Added noise:19.624265   Cheetah 42.624265
586 Added noise:-9.032787   Chicken 66.967213
587 Added noise:-29.396239  Chimpanzee      -21.396239
588 Added noise:-11.834371  Chinchilla      57.165629
589 Added noise:34.078909   Chough  69.078909
590 Added noise:5.546933    Clam    88.546933
591 Added noise:29.451771   Capybara        69.451771
592 Added noise:2.856111    Cobra   76.856111
593 Added noise:-0.700628   Cockroach       16.299372
594 Added noise:3.063374    Cod     80.063374
595 Added noise:-8.927342   Cormorant       43.072658
596 Added noise:10.923060   Coyote  41.923060
597 Added noise:1.814030    Crab    15.814030
598 Added noise:-18.547510  Crane   21.452490
599 Added noise:6.000231    Crocodile       52.000231
600 Added noise:-1.101399   Crow    97.898601
601 Added noise:-7.423426   Curlew  36.576574
602 Added noise:9.604109    Deer    24.604109
603 Added noise:2.048539    Dinosaur        91.048539
604 Added noise:3.369599    Dog     39.369599
605 Added noise:3.854287    Dogfish 101.854287
606 Added noise:0.819617    Dolphin 20.819617
607 Added noise:5.006280    Donkey  61.006280
608 Added noise:-7.830403   Dove    82.169597
609 Added noise:-27.546720  Dragonfly       -22.546720
610 Added noise:2.114169    Duck    77.114169
611 Added noise:36.470799   Eagle   59.470799
612 Added noise:-1.601299   Echidna 47.398701
613 Added noise:12.674892   Eel     95.674892
614 Added noise:-19.480890  Elephant        35.519110
615 Added noise:-0.884935   Elk     21.115065
616 Added noise:20.680674   Emu     27.680674
617 Added noise:3.158528    Falcon  19.158528
618 Added noise:13.770356   Ferret  104.770356
619 Added noise:0.694302    Finch   80.694302
620 Added noise:-19.396868  Fish    1.603132
621 Added noise:2.803834    Flamingo        58.803834
622 Added noise:3.436229    Fly     13.436229
623 Added noise:-23.440703  Fox     4.559297
624 Added noise:4.077606    Frog    33.077606
625 Added noise:-1.887445   Gazelle 17.112555
626 Added noise:4.931220    Gerbil  77.931220
627 Added noise:1.087305    Giraffe 46.087305
628 Added noise:0.631703    Gnat    5.631703
```

```
Added noise:2.466833    Goat    22.466833
Added noise:-9.478603   Goldfinch       18.521397
Added noise:-1.551533   Goldfish        43.448467
Added noise:-3.149230   Goose   35.850770
Added noise:4.692250    Gorilla 68.692250
Added noise:14.223974   Grasshopper     36.223974
Added noise:13.613542   Gull    20.613542
Added noise:9.034664    Hamster 39.034664
Added noise:6.520177    Hare    16.520177
Added noise:0.874181    Hawk    48.874181
Added noise:1.251442    Hedgehog        61.251442
Added noise:5.811212    Heron   78.811212
Added noise:5.365779    Herring 87.365779
Added noise:-0.600121   Hippopotamus    95.399879
Added noise:3.226949    Hornet  85.226949
Added noise:9.115452    Horse   47.115452
Added noise:-2.783325   Hummingbird     81.216675
Added noise:6.455428    Hyena   45.455428
Added noise:-3.968136   Jackal  8.031864
Added noise:3.259312    Jaguar  78.259312
Added noise:16.263379   Jay     91.263379
Added noise:1.891539    Kangaroo        46.891539
Added noise:57.015686   Koala   144.015686
Added noise:4.114456    Lark    95.114456
Added noise:5.810608    Lemur   38.810608
Added noise:5.925662    Leopard 45.925662
Added noise:3.929627    Lion    3.929627
Added noise:20.590343   Llama   87.590343
Added noise:3.922280    Lobster 66.922280
Added noise:4.094501    Locust  20.094501
Added noise:-0.565420   Mallard 92.434580
Added noise:4.074100    Manatee 23.074100
Added noise:6.371621    Marten  78.371621
Added noise:2.629748    Meerkat 48.629748
Added noise:6.924737    Mole    79.924737
Added noise:-22.169708  Monkey  75.830292
Added noise:1.104019    Moose   87.104019
Added noise:3.089674    Mosquito        6.089674
Added noise:-0.572221   Mouse   63.427779
Added noise:-1.389947   Mule    92.610053
Added noise:15.630441   Narwhal 90.630441
Added noise:5.972588    Newt    7.972588
Added noise:18.484840   Nightingale     105.484840
Added noise:5.060864    Octopus 79.060864
```

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673 Added noise:5.568717    Opossum 84.568717
674 Added noise:34.146389   Ostrich 90.146389
675 Added noise:-0.804352   Otter   50.195648
676 Added noise:2.753591    Owl     79.753591
677 Added noise:0.836282    Ox      81.836282
678 Added noise:2.269158    Oyster  44.269158
679 Added noise:1.863705    Panther 91.863705
680 Added noise:6.266325    Parrot  102.266325
681 Added noise:10.181417   Peafowl 14.181417
682 Added noise:0.636729    Pelican 58.636729
683 Added noise:1.914786    Penguin 74.914786
684 Added noise:-7.434327   Pheasant        19.565673
685 Added noise:7.694542    Pig     63.694542
686 Added noise:33.963961   Pigeon  113.963961
687 Added noise:10.683371   Porcupine       20.683371
688 Added noise:-3.616547   Porpoise        31.383453
689 Added noise:-4.507510   Quail   81.492490
690 Added noise:7.704579    Rabbit  107.704579
691 Added noise:3.789846    Raccoon 19.789846
692 Added noise:-1.022422   Rail    5.977578
693 Added noise:-13.620866  Ram     16.379134
694 Added noise:10.658370   Rat     94.658370
695 Added noise:-9.028745   Raven   40.971255
696 Added noise:13.741062   Rhinoceros      99.741062
697 Added noise:1.253142    Salamander      22.253142
698 Added noise:-14.844231  Salmon  0.155769
699 Added noise:35.019474   Sardine 101.019474
700 Added noise:7.232440    Scorpion        82.232440
701 Added noise:12.384777   Seahorse        83.384777
702 Added noise:-15.812311  Seal    40.187689
703 Added noise:12.722069   Shark   64.722069
704 Added noise:11.654935   Sheep   110.654935
705 Added noise:24.905902   Shrew   69.905902
706 Added noise:-3.771565   Shrimp  80.228435
707 Added noise:-34.587962  Skunk   64.412038
708 Added noise:13.563097   Snail   64.563097
709 Added noise:1.268744    Snake   38.268744
710 Added noise:2.623525    Spider  98.623525
711 Added noise:0.739376    Squid   90.739376
712 Added noise:47.287684   Squirrel        139.287684
713 Added noise:-22.262713  Starling        57.737287
714 Added noise:-3.262939   Stingray        92.737061
715 Added noise:-4.110494   Stinkbug        26.889506
716 Added noise:1.276034    Stork   40.276034
```

```
Added noise:3.203149    Swallow 5.203149
Added noise:7.769937    Swan    75.769937
Added noise:0.882838    Tapir   53.882838
Added noise:-2.206818   Tiger   44.793182
Added noise:-6.611757   Toad    75.388243
Added noise:10.006503   Trout   61.006503
Added noise:15.809723   Turkey  72.809723
Added noise:-3.304991   Turtle  6.695009
Added noise:3.381575    Viper   31.381575
Added noise:-0.121260   Vulture 90.878740
Added noise:4.746634    Walrus  98.746634
Added noise:2.432170    Wasp    53.432170
Added noise:15.807208   Weasel  35.807208
Added noise:-8.583527   Whale   78.416473
Added noise:2.935602    Wolf    83.935602
Added noise:13.584202   Wolverine       49.584202
Added noise:2.603746    Wombat  86.603746
Added noise:2.692741    Woodcock        56.692741
Added noise:4.441045    Woodpecker      11.441045
Added noise:20.720977   Worm    62.720977
Added noise:0.802158    Wren    55.802158
Added noise:-9.491801   Yak     50.508199
Added noise:9.071580    Zebra   16.071580
Animals which carrots cost > 55 (Under DP): 95
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```

(二) 直方图发布 testhist 运行结果

```
erwinzhou@erwinzhou-virtual-machine:~/lab/labcodes/DataSecurity/Lab05/experiment1$ ./testhist
Under privacy budget 10.000000, sanitized original bucket with laplace noise:
Added noise:0.049987    20-30   405.049987
Added noise:0.070591    30-40   436.070591
Added noise:-0.252260   40-50   420.747740
Added noise:-0.184343   50-60   456.815657
Added noise:0.265684    60-70   463.265684
==================Using neighbour dataset==================
Added noise:0.354999    20-30   405.354999
Added noise:0.917567    30-40   435.917567
Added noise:0.553866    40-50   421.553866
Added noise:0.069505    50-60   457.069505
Added noise:0.850041    60-70   463.850041
============================================================
```

```
Under privacy budget 0.100000, sanitized original bucket with laplace noise:
Added noise:3.934012    20-30   408.934012
Added noise:-2.139818   30-40   433.860182
Added noise:-6.059983   40-50   414.940017
Added noise:-0.321125   50-60   456.678875
Added noise:2.618170    60-70   465.618170
==================Using neighbour dataset==================
Added noise:2.978226    20-30   407.978226
Added noise:-0.050931   30-40   434.949069
Added noise:2.621044    40-50   423.621044
Added noise:3.562499    50-60   460.562499
Added noise:1.238240    60-70   464.238240
============================================================
```

参考文献