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Herd Immunity: A Classroom Experiment

Outbreaks of dangerous, preventable diseases have drawn attention to individuals who fail to obtain available and effective vaccines. This classroom experiment demonstrates the basic cost-benefit tradeoff inherent in vaccination. As more students obtain a costly vaccine, the likelihood of a non-immunized student catching the disease declines; non-vaccinating students obtain herd immunity. In equilibrium, a substantial fraction of students fail to obtain the vaccine. In addition to highlighting a genuine public health issue, the experiment can also be used more generally to illustrate the nature of externalities and the public goods problem.

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1. Introduction

Herd immunity exists when the proportion of a population vaccinated against a disease is sufficiently high that unvaccinated members of that population are unlikely to contract that disease.[1] Recent outbreaks of whooping cough and measles provide interesting context for questions about the value of herd immunity. According to the Centers for Disease Control, reported cases of whooping cough in the United States averaged 2,654 between 1970 and 1990, yet in 2014 there were over 32,000 reported cases.[2] Over 9,000 of those cases were reported in California.[3] Measles, declared eliminated as an endemic illness in 2000, resurged in 2014: Six hundred sixty seven cases stemming from 27 unique outbreaks were reported to the Centers for Disease Control. By comparison, the average number of cases between 2000 and 2013 was less than 100 per year.[4]

These diseases are completely avoidable if everyone obtains the appropriate vaccine. Yet enough people choose not to be vaccinated that these diseases present a genuine public health concern.[5]

This experiment demonstrates one reason why significant numbers of people opt not to vaccinate themselves or their children. The experiment asks participants to make a straightforward decision: "Do I obtain a vaccine or not?"

In this experiment, obtaining a vaccine can potentially provide great benefits, but those benefits come at some cost. To a particular individual, the overall cost-effectiveness of vaccination depends on the number of other participants who choose to obtain the vaccine. If very few receive the vaccine, the disease can spread easily and the probability of an unimmunized individual catching the disease will be high. If a large proportion of other participants receive the vaccine, then there are relatively few people from whom unvaccinated participants can catch the disease; the probability of an unvaccinated person catching the disease will be low.

2. Literature Review

Several studies have documented a positive impact of classroom experiments on learning, although the literature on the impact of classroom experiments on student learning is somewhat mixed. It is possible that the lack of consensus stems in part from the heterogeneity of experiments employed in various studies, differences in the manner in which the experiments are administered, and the richness of the post-experiment discussion linking the experiment to theory.

Cardell et al. (1996) studied the impact of implementing multiple experiments in a principles of microeconomics course, and found that adding experiments did not make a statistically significant difference in student learning gains, as measured by the Test of Understanding in College Economics (TUCE).

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[1] Department of Health and Human Services at http://www.vaccines.gov/basics/protection/.

[2] See Centers for Disease Control at http://www.cdc.gov/pertussis/surv-reporting/cases-by-year.html.

[3] See Centers for Disease Control at http://www.cdc.gov/mmwr/preview/mmwrhtml/mm6348a2.htm.

[4] See Centers for Disease Control at http://www.cdc.gov/measles/cases-outbreaks.html.

[5] Outbreaks of preventable diseases are not unique to the United States. Even polio, once thought to be almost completely eradicated, is staging a resurgence in parts of Africa and Asia. See Centers for Disease Control Morbidity and Mortality Weekly Report, May 22, 2015 at http://www.cdc.gov/mmwr/preview/mmwrhtml/mm6419a5.htm.

In direct contrast, Emerson and Taylor (2004) studied multiple sections of a principles of microeconomics course, some sections utilizing experiments in the classroom experience and other sections not. Emerson and Taylor found that students in sections utilizing experiments in the classroom experienced larger gains in TUCE scores than students in sections without experiments. (They found no significant impact of experiments on performance on a common, departmental final exam; nor did the use of experiments appear to affect student course evaluations.) Emerson and Taylor also found that incorporating experiments produced outsize TUCE gains for students with varied characteristics: Experiments produced disproportionately large gains for low-ability/achievement students and for females, though experiments did not produce gains for nonwhites. In fact, nonwhite students in experimental sections made significantly smaller gains on the TUCE than nonwhite students in non-experimental sections.

Durham, McKinnon, and Schulman (2007) also found that the impact of experiments on learning differs by student characteristic. In their study, experiments produced significant comprehension gains, as measured by performance on embedded exam questions, for multimodal and kinesthetic learners. Read-write learners, in contrast, did just as well with traditional lectures and discussion. Durham, McKinnon, and Shulman report that more lengthy and complex experiments appear to have a stronger positive impact on student learning. Additionally, they report that students' attitudes (as measured by survey) are significantly improved through the use of experiments.

Dickie (2007) provides additional evidence in support of classroom experiments. Dickie found that experiments without grade incentives produced significantly higher post-test TUCE scores and larger TUCE gains between a pre-test and a post-test. However, Dickie reports that incorporating grade incentives into the experiment may have an offsetting effect on learning.

The concept of herd immunity can be traced as far back as Topley and Wilson (1923), but only in recent decades has the term been commonly used. The resurgence of whooping cough and measles has brought attention to issues of relying on herd immunity for protection against contagious diseases. Organizations and teachers have developed several classroom exercises devoted to exploring those issues. The Centers for Disease Control offers a thorough lesson plan with an integrated game, tailored to middle-school students, that can be completed in 2 to 3 hours.[6] The Public Broadcasting System (PBS) has also developed a 1 to 2 hour lesson plan to accompany its series, *The Vaccine War*.[7] Beyond classroom exercises, there are several herd immunity simulations available online.[8] Each of these activities explores how a contagious disease spreads across time. This experiment, in contrast, focuses not on the spread of the disease, but on the individual decision to obtain or not to obtain a vaccine. It highlights concepts commonly discussed in the economics classroom: Nash equilibrium, cost-benefit analysis, externalities, free-riding behavior, and the explicit calculation of expected values.

3. Description of the Experiment

The essence of the herd immunity experiment is as follows: A particularly potent virus is circulating, and there are fears it will invade your classroom. A vaccine is now on the market, and your students must choose whether or not to obtain it. Receiving the vaccination is costly, but students who obtain the vaccine are guaranteed not to contract the virus.

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[6] This lesson plan, created by Joye Hopkins and Theresa Pinilla, can be found at http://www.cdc.gov/scienceambassador/lesson-plans/2013-herd-immunity.pdf.

[7] See http://www.pbs.org/wgbh/pages/frontline/teach/vaccine/lesson.html .

[8] See http://fred.publichealth.pitt.edu/measles/ and http://www.software3d.com/Home/Vax/Immunity.php for examples.

Students who do not obtain the vaccine may or may not get sick. Getting sick is costly—more costly than obtaining the vaccine. The probability of a particular unimmunized student catching the disease depends on the proportion of that student's classmates who obtain the vaccine, and is given by the following formula:

$$P(\text{Illness}) = 100\% \times \left(\frac{\# \text{ in class} - \# \text{ vaccinated} - 1}{\# \text{ in class} - 1} \right)$$

In this formula, the one in both numerator and denominator denotes the particular non-vaccinator in question. Thus, for a particular student, the denominator simply represents the number of classmates that student has; the numerator represents the number of those classmates who did not obtain the vaccine; and the entire formula yields the percentage of that student's classmates who did not receive the vaccine.

This expression captures the essential piece of realism mentioned in the introduction: For a given class size, the likelihood of a particular unimmunized student getting ill is directly related to the number of that student's classmates who choose not to obtain the vaccine. If very few of a student's classmates are immunized, then the student is very likely to get sick; if almost all of a student's classmates have obtained the vaccine, then the student is likely to remain well even if that student does not obtain the vaccine.[9]

In this version of the formula, the probability of a particular student catching the illness is linear in the proportion of that student's classmates who did not obtain the vaccine. This convention is adopted simply because it makes each student's cost-benefit trade-off easier to calculate. A more general version of the formula that allows for nonlinearity in the proportion of non-vaccinators is presented in Appendix A.

4. Administration

Hand out the instructions one class period in advance so students can explore the formula before offering their responses. (A set of sample instructions is included in Appendix B.) On the day you administer the experiment, you may find it useful to talk through the formula with students to be sure they understand the parameters of the game.

The actual administration is quite simple: Because students do not have to interact with one another in any meaningful way, this experiment reduces to a polling exercise in which you ask your students whether they would like to be vaccinated or not. You may receive responses by clicker, on paper, by email, or by any other means that suits your preferences and that allows you to keep track of each individual's response.

When all responses have been received, tabulate the number immunized and apply the formula above to determine the probability of an unvaccinated student contracting the disease. Then, generate a random number between 0 and 100 and compare it to the probability you calculated.[10] If the random number you generated is below the non-vaccinators' probability of

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[9] Note that if all of a particular student's classmates obtain the vaccine, then there is zero probability of the student getting ill. Likewise, if none of the student's classmates obtain the vaccine, there is a 100-percent probability of the student getting ill. Although neither of these extreme cases is entirely realistic, in-class experience indicates that the proportion of students choosing the vaccine is generally quite far from either extreme.

[10] There are many free random number generators available online. If you are a spreadsheet user, there is a random number generator built into Microsoft Excel: Try "=randbetween(0,100)." Some versions of Excel may require you to activate the Analysis Toolpack add-on for this function to be active.

illness, then non-vaccinators will contract the disease.

That process assumes the disease is so virulent that if one unimmunized student contracts it, it will quickly spread to all the other non-vaccinators. However, if your class is small, it is certainly possible to generate a different random number for each non-vaccinator. Consider giving your students more than one chance to participate in this experiment. Students placed in unfamiliar situations can learn by experience, and a second or third attempt at the exercise may be useful.

5. Theoretical and Actual Outcomes

Determining the theoretical outcome of this game is straightforward. Consider the game from the standpoint of a particular student trying to decide whether to obtain the vaccine or not. If the student decides against the vaccine, that student's probability of contracting the disease depends on the number of that student's classmates who obtain the vaccine. In this example, obtaining the vaccine costs 500 points, and getting ill costs unimmunized students 1500 points. (Suggestions for assigning points will be offered in the next section.)

Suppose that the student decides to obtain the vaccine, which guarantees immunity. No matter how many classmates obtain the vaccine, the student will incur a loss of 500 points. The dotted line in Figure 1 indicates that cost.

The dashed line in Figure 1 indicates the expected payoff the student will receive if that student does not obtain the vaccine, expressed as a function of the number of classmates who have been immunized. At the endpoint where no classmates are vaccinated, the student is guaranteed to catch the disease and will lose 1,500 points. At the endpoint where all classmates are vaccinated, the student is guaranteed not to get sick and illness costs will be zero; the student has obtained complete herd immunity.

Figure 1 - Herd Immunity: A Graphical Model

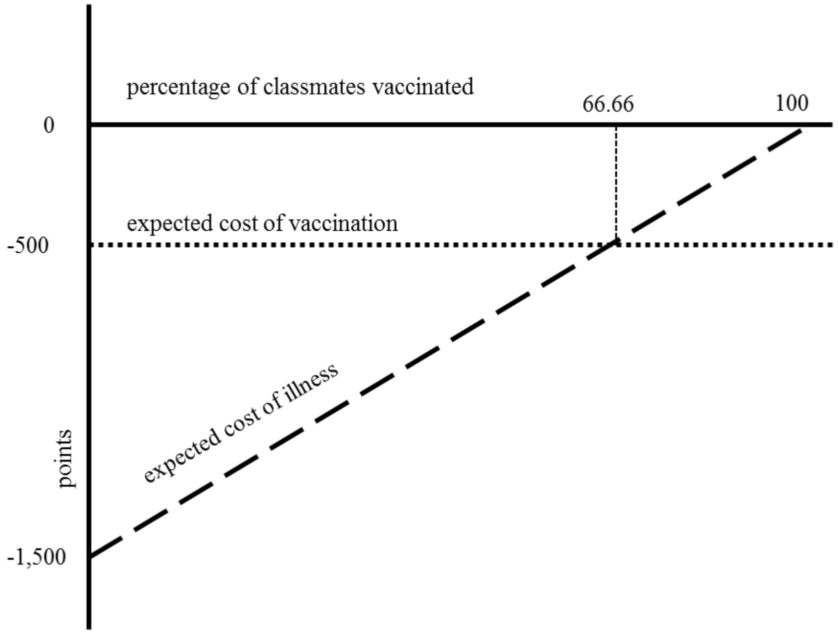

Table 1 - Outcomes from Classroom Trials, 2010-2015[a]

Semester	**Number Receiving Vaccine**	**Number Not Receiving Vaccine**	**Proportion Vaccinating**
Fall 2010	23	11	67.6%
Summer 2011	11	5	68.8%
Fall 2011a	22	14	61.1%
Fall 2011b	21	11	65.6%
Spring 2012	19	10	65.5%
Summer 2012	9	4	69.2%
Fall 2012a	15	9	62.5%
Fall 2012b	18	10	64.2%
Spring 2014a	12	4	75.0%
Spring 2014b	12	5	70.5%
Spring 2015	19	9	67.9%

The expected costs of obtaining the vaccine and not obtaining the vaccine are equal at the intersection of dotted and dashed lines. That point is found where exactly 2/3 of the student's classmates obtain the vaccine; there, the probability of catching the disease is exactly 1/3. That outcome is a Nash equilibrium: If fewer than 2/3 of the class obtains the vaccine, the expected cost of not vaccinating is greater than the cost of the vaccine and the proportion of vaccinators should rise. If more than 2/3 of the class obtains the vaccine, the expected cost of not vaccinating is less than the cost of the vaccine and the proportion of vaccinators should fall. Thus, consistent with reality, the experiment predicts that some people will obtain the vaccine and others will make a cost-benefit calculation not to.

Classroom experience largely supports the theoretical prediction of the model. We administered this experiment in a general education course, Economic Analysis of Social Issues. As can be seen in Table 1 which reports the results of this experiment from the past several years, the final-round student response rate varies little from the predicted 2/3 vaccination rate.

6. Discussion Points

The herd immunity experiment is a convenient forum for discussing several topics often covered in microeconomics, public policy, and health economics courses.

Externalities: Suppose that a particular student chooses to obtain the vaccine. The student receives some private benefit from that choice. But that choice also results in a reduction in the probability that unvaccinated students will contract the illness. The student's decision to obtain the vaccine confers an external benefit on the student's unvaccinated classmates. The analysis of this particular positive externality is easily generalizable to apply in other contexts: One obvious extension is the analysis of the benefits of education: Most of those benefits are captured

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[a] Each administration of the experiment included three rounds. Reported results are from the final round of each administration.

by the student, but some of the benefits also spill over to the rest of society.

Public Goods: When a student decides to obtain the vaccine, the external benefits are both nonrival and nonexcludable. In other words, vaccination is a public good, and as such, is likely to be underprovided by private individuals. Consider a class of 19 students that has reached the theoretical equilibrium of the game, with 12 students obtaining the vaccine and six choosing not to obtain the vaccine. Now, consider the marginal 19th student: That student's expected loss from choosing not to obtain the vaccine is equal to the cost of obtaining the vaccine. In other words, that student is indifferent between being a non-vaccinator (expected cost = 1,500 × (6/18) = 500) and vaccinating (cost = 500). Private individuals, left to their own initiative, will produce an outcome with six or seven unvaccinated citizens.

To see the potential role for intervention, imagine a benevolent, omniscient central planner who seeks to minimize the sum over all individuals of expected disease cost and disease avoidance cost. The planner's calculations can be seen in Table 2.

Table 2: Total Social Costs for Various Outcomes[b]

Number Vaccinated	**Number Unvaccinated**	**Total Vaccination Costs**	**Expected Illness Costs**	**Total Social Costs**
0	19	0	28,500	28,500
1	18	500	25,500	26,000
2	17	1,000	22,667	23,667
3	16	1,500	20,000	21,500
4	15	2,000	17,500	19,500
5	14	2,500	15,167	17,667
6	13	3,000	13,000	16,000
7	12	3,500	11,000	14,500
8	11	4,000	9,167	13,167
9	10	4,500	7,500	12,000
10	9	5,000	6,000	11,000
11	8	5,500	4,667	10,167
12	7	6,000	3,500	9,500
13	6	6,500	2,500	9,000
14	5	7,000	1,667	8,667
15	4	7,500	1,000	8,500
16	3	8,000	500	8,500
17	2	8,500	167	8,667
18	1	9,000	0	9,000
19	0	9,500	0	9,500

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[b] Assumes a class of 19 students, with a 500-unit cost of obtaining vaccine and a 1,500-unit cost of getting ill.

In Table 2, Columns 1 and 2 show the number of students in a class of 19 who are vaccinated and unvaccinated, respectively. Column 3 shows total vaccination costs, which equal 500 times the number vaccinated. Column 4, expected illness costs, are calculated as follows:[11]

$$\text{Expected Illness Costs} = \text{Number Unvaccinated} \times 1500 \times \frac{\text{Number Unvaccinated} - 1}{18}$$

The sum of expected illness costs and illness-avoidance (vaccination) costs over all individuals is maximized when no one vaccinates. In that case, everyone gets sick with certainty at a cost of 1,500 each. Total costs are *minimized* when three or four people do not obtain the vaccine. At that point, the probability of illness is sufficiently low that the 500-point cost of the vaccine is not justified. Recall that the equilibrium outcome in this game is for six or seven students to remain unvaccinated; private individuals acting on their own initiative tend to vaccinate less than is socially desirable.

Notice that in the optimal range of vaccination (three to four unvaccinated students in a class of 19), expected illness costs are still 500 to 1,000. In other words, the ideal level of vaccination is not, as many would argue, 100%, and the ideal level of illness is not zero. You may ask the students to ponder how those costs will be distributed across society. Who will bear those costs? Because they cannot be shared equally, this may be used as an opportunity to discuss tradeoffs between efficiency and equity.

Free-Riding Behavior: Free riding exists when someone enjoys the benefits of an activity without bearing a proportionate share of the costs (see Baumol (1953)). Because of the non-excludable nature of the external benefits of immunization, individuals have an incentive to free-ride on the immunization of others. Indeed, this is the essence of the experiment, which is a specific application of the more general notion of free-ridership: "Do I obtain the vaccine, or do I trust that enough of my classmates will obtain the vaccine that I won't get sick?" This experiment provides a simple platform to explore the nature of free-riding that is easily extensible to other situations in which incentives to free ride exist.

Public Policy and Graphical Analysis: The graphical framework can be used to illustrate the effects of various public policies to encourage vaccination. For example, government often subsidizes the cost of vaccine. The subsidy reduces the cost of obtaining the vaccine, which can be illustrated by shifting the dotted line in Figure 1 upward. That, in turn, moves the equilibrium toward the right: More people get vaccinated. In classroom trials, a 100-percent government subsidy resulted in nearly a 100-percent compliance rate. You might, as an exercise, attempt to find the level of subsidization that would steer the class to the efficient level of vaccination described above.

Government might also make vaccinations mandatory and impose some penalty for failing to obtain them. That changes the payouts to non-vaccinators, increasing the expected cost of failing to obtain the vaccine and shifting the dashed line in Figure 1 downward and the equilibrium to the right. The result is an increase in the proportion of the population who obtain the vaccine.

Linking the Experiment and the Real World: Discussing the simplifications embedded in this experiment can help your students make valuable connections between this classroom game and the real world.

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[11] More generally, expected illness costs for a class are given by:

$$\text{Expected Illness Costs} = \text{Number Unvaccinated} \times \text{Cost of Getting Ill} \times \frac{\text{Number Unvaccinated} - 1}{\text{Number of Students} - 1}$$

This experiment, for example, assumes that people are homogeneous. In reality, people are not, and some individuals may be unable to receive certain vaccinations for legitimate medical reasons. Herd immunity can be very valuable to those individuals.

The experiment description also simplifies the nature of the cost of obtaining the vaccine. That cost is described as a combination of the dollar cost of the vaccine plus the pain and suffering caused by the injection. But health insurance and public health clinics make many vaccines available at little or no out-of-pocket cost; the main cost may more accurately reflect the time and hassle involved in obtaining the vaccine.

Finally, it is useful to discuss individuals' fears about the safety of vaccines. Some of those fears are scientifically sound (recipients may have adverse reactions to vaccines); others may not be. Valid or not, these fears persist and lead to lower vaccination rates than many public health experts deem ideal.

7. Suggestions for Scoring

In the experiment as described, students can only break even or lose. To make this experiment an opportunity rather than a penalty, begin by awarding enough points to cover students' losses. The assignment can be normed to 100 points quite easily by giving each student 100 points to begin, then charging, say, 15 points for the vaccine and 45 points to non-vaccinators who get ill.[12] Alternatively, you might make the assignment count toward extra credit on an exam. Give five extra credit points to begin; charge one for the vaccine and three for getting ill.

There is no particular magic in the 1 to 3 ratio: You can adjust this as you see fit. For example, you might charge 10 points for the vaccine and 20 points for contracting the illness. Such an adjustment only requires that you compute the corresponding equilibrium.

8. Conclusion

The herd immunity experiment is a classroom game that sheds light on an important public policy question: Why do some people fail to obtain vaccines that could protect themselves and others? This experiment suggests that, in addition to religious objections or fears of an adverse reaction, individuals may rationally choose to obtain or avoid the vaccine based on a straightforward cost-benefit calculation. The experiment is a convenient vehicle to demonstrate the distinction between private and external benefits and the notion of free-ridership, and to illustrate the potential for government intervention to increase social well-being. Students leave the experiment with a better understanding of both economic theory and a real-world public health issue.

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[12] You can set those fees at whatever level you wish—it all depends on how generous you wish to be with your grades. You could just as easily set the fee for the vaccine at 30 points and the cost of the illness at 90 points.

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Appendix A: A More General Formula

In the original formulation, the probability of catching the disease is linear in the number of classmates choosing to obtain the vaccine. A more general exponential version can be given as:

$$P(\text{Illness}) = 100\% \times \left(\frac{\#\text{ in class} - \#\text{ vaccinated} - 1}{\#\text{ in class} - 1} \right)^{\alpha}$$

where α is a positive number chosen by the administrator. Generally speaking, α > 1 reasonably implies that the risk of contracting the illness grows exponentially the greater the fraction of unvaccinated participants. That is a reasonable assumption, but not critical: You could plausibly argue that a disease is so contagious that even a few unvaccinated students in the population present a significant risk. In that case, set α < 1.

Note that the extreme cases in this exponential version are the same as in the linear version (which is just the special case α = 1): When nobody else obtains the vaccine, the probability of an unvaccinated student contracting the illness is still 100 percent; when everybody else obtains the vaccine, the probability of an unvaccinated individual contracting the illness is zero.

Appendix B: Sample Student Instructions

Herd Immunity Experiment

A particularly potent strain of the flu virus has been discovered in your class. In an effort to avoid a pandemic, the Centers for Disease Control put their best team to work developing a vaccine. That team's vaccine is now on the market. Today, you must decide whether to obtain the vaccine.

Framework:

- Receiving the vaccination is both painful and expensive. The cost of the vaccine, plus the cost of your pain and suffering, is 500 points total.
- If you obtain the vaccine, you will not contract the virus. You have complete immunity.
- You may choose not to obtain the vaccine.
- If you do not obtain the vaccine, there is some probability that you will catch the disease. That probability is given by the following formula:

$$P(\text{Illness}) = 100\% \times \left(\frac{\#\text{ in class} - \#\text{ vaccinated} - 1}{\#\text{ in class} - 1} \right)$$

- If you catch the disease, you will incur 1500 points worth of pain, suffering, and medical expenses.

Administration:

- When asked, submit your choice to your instructor.
- Your options are "Obtain the vaccine," or "Don't obtain the vaccine."
- Once all responses are received, your instructor will compute the probability of those choosing "Don't obtain the vaccine" contracting the disease. Call that probability P.
- Your instructor will then determine whether unvaccinated individuals will contract the disease by generating a random number, R, between 0 and 100.
- If $R < P$, those who did not obtain the vaccine will contract the disease.
- If $R \geq P$, those who did not obtain the vaccine will not contract the disease
- The game will be repeated three times.