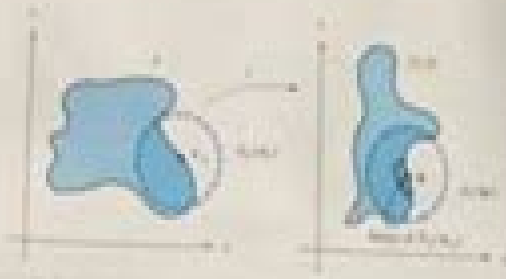

To illustrate the application of the squeeze rule technique in Theorem 4, we consider the following examples.

example 12

Show that $\lim_{(x,y)\to(0,0)} x = 0$ using the ε–δ method.

solution

Note that if $\delta \le 1$, $|x| < \delta \Rightarrow |x| < 1 \Rightarrow |x| < \sqrt{x^2+y^2} < 1$ implies $|x-0| = |x| < \sqrt{x^2+y^2} < \delta$. Thus, if $\|(x,y)-(0,0)\| < \delta$, then $|x-0| < \varepsilon$ is also true. Hence $\delta = \min\{1, \varepsilon\}$ will be required to find $\delta > 0$. A symmetric dependency on ε with the property that $|x-0| < \delta \Rightarrow |x| < \varepsilon$ implies $|x-0| < \varepsilon$. What are we to pick as our δ? From the preceding considerations, we see that the choice of $\delta = \varepsilon$ does. If $|x| < \delta = \varepsilon$, then $\|(x,y)-(0,0)\| < \delta$ implies $|x-0| < \varepsilon$. This shows that $\lim_{(x,y)\to(0,0)} x = 0$. Choosing $\delta = \varepsilon$, we could have also chosen $\delta = \varepsilon/2$ or $\varepsilon/3$, but any one is sufficient to find just one δ satisfying the requirements of the definition of a limit. ■

example 13

Consider the function

$$f(x,y) = \frac{\sin(x^2+y^2)}{x^2+y^2}$$

Even though f is not defined at $(0,0)$, determine whether $f(x,y)$ approaches some number as (x,y) approaches $(0,0)$.

solution

From one-variable calculus or L'Hôpital's rule we know that

$$\lim_{t\to 0} \frac{\sin t}{t} = 1$$

Thus, it is reasonable to guess that

$$\lim_{(x,y)\to(0,0)} f(x,y) = \lim_{(x,y)\to(0,0)} \frac{\sin(x^2+y^2)}{x^2+y^2} = 1$$

Indeed, because $\lim_{t\to 0} \sin t/t = 1$, given $\varepsilon > 0$ we are able to find $\delta = \delta_1$ with $0 < \delta < 1$, such that $0 < |x| < \delta$ implies that $\left|\frac{\sin x}{x} - 1\right| < \varepsilon$. If $0 < \|(x,y)\| < \delta$, then $0 < |x|^2 + y^2 < \delta^2$, and therefore

$$|f(x,y) - 1| = \left|\frac{\sin(x^2+y^2)}{(x^2+y^2)} - 1\right| < \varepsilon$$

Figure 5.5 (a) Graph of the function $f(x,y) = \frac{\sin(x^2+y^2)}{x^2+y^2}$ (b) Contour plot of f

Thus, finally, $\lim_{(x,y)\to(0,0)} f(x,y) = 1$. If we plot $f(x,y) = \frac{\sin(x^2+y^2)}{x^2+y^2}$ on a computer, we get a graph that is indeed well-behaved near $(0,0)$, as in Figure 5.5 (a). ■

example 14

Show that

$$\lim_{(x,y)\to(0,0)} \frac{x}{\sqrt{x^2+y^2}} = 0$$

solution

We must show that $x/\sqrt{x^2+y^2}$ is small when (x,y) is close to the origin. To do this, we use the following inequality:

$$0 \le \frac{x^2}{\sqrt{x^2+y^2}} \le \frac{x^2+y^2}{\sqrt{x^2+y^2}} = \sqrt{x^2+y^2} \qquad \text{(because } y^2 \ge 0\text{)}$$

Given $\varepsilon > 0$, choose $\delta = \varepsilon$. Then $\|(x,y)-(0,0)\| = \sqrt{x^2+y^2}$, and $|x| \le \sqrt{x^2+y^2}$ implies that

$$\left|\frac{x}{\sqrt{x^2+y^2}} - 0\right| = \frac{x^2}{\sqrt{x^2+y^2}} \le \sqrt{x^2+y^2} = \|(x,y)-(0,0)\| < \delta = \varepsilon$$

Thus, the conditions of Theorem 4 have been fulfilled and the limit is verified.

example 15

(a) Show

$$\lim_{(x,y)\to(0,0)} x^2 \ln(x^2+y^2)$$

exists. [See Figure 5.5 (Plot).]

(b) Prove that (see Figure 5.5 (Plot))

$$\lim_{(x,y)\to(0,0)} \frac{2x^2 y}{x^2+y^2} = 0$$

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Table of Contents Study Guide Vector Calculus Sixth Edition

1. Understanding the eBook Study Guide Vector Calculus Sixth Edition
    - The Rise of Digital Reading Study Guide Vector Calculus Sixth Edition
    - Advantages of eBooks Over Traditional Books
2. Identifying Study Guide Vector Calculus Sixth Edition
    - Exploring Different Genres
    - Considering Fiction vs. Non-Fiction
    - Determining Your Reading Goals
3. Choosing the Right eBook Platform
    - Popular eBook Platforms
    - Features to Look for in an Study Guide Vector Calculus Sixth Edition
    - User-Friendly Interface
4. Exploring eBook Recommendations from Study Guide Vector Calculus Sixth Edition

- Personalized Recommendations
- Study Guide Vector Calculus Sixth Edition User Reviews and Ratings
- Study Guide Vector Calculus Sixth Edition and Bestseller Lists

5. Accessing Study Guide Vector Calculus Sixth Edition Free and Paid eBooks
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   - Study Guide Vector Calculus Sixth Edition Budget-Friendly Options
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   - ePub, PDF, MOBI, and More
   - Study Guide Vector Calculus Sixth Edition Compatibility with Devices
   - Study Guide Vector Calculus Sixth Edition Enhanced eBook Features
7. Enhancing Your Reading Experience
   - Adjustable Fonts and Text Sizes of Study Guide Vector Calculus Sixth Edition
   - Highlighting and Note-Taking Study Guide Vector Calculus Sixth Edition
   - Interactive Elements Study Guide Vector Calculus Sixth Edition
8. Staying Engaged with Study Guide Vector Calculus Sixth Edition
   - Joining Online Reading Communities
   - Participating in Virtual Book Clubs
   - Following Authors and Publishers Study Guide Vector Calculus Sixth Edition
9. Balancing eBooks and Physical Books Study Guide Vector Calculus Sixth Edition
   - Benefits of a Digital Library
   - Creating a Diverse Reading Collection Study Guide Vector Calculus Sixth Edition
10. Overcoming Reading Challenges
    - Dealing with Digital Eye Strain
    - Minimizing Distractions
    - Managing Screen Time
11. Cultivating a Reading Routine Study Guide Vector Calculus Sixth Edition
    - Setting Reading Goals Study Guide Vector Calculus Sixth Edition
    - Carving Out Dedicated Reading Time
12. Sourcing Reliable Information of Study Guide Vector Calculus Sixth Edition

- Fact-Checking eBook Content of Study Guide Vector Calculus Sixth Edition
- Distinguishing Credible Sources

13. Promoting Lifelong Learning
    - Utilizing eBooks for Skill Development
    - Exploring Educational eBooks
14. Embracing eBook Trends
    - Integration of Multimedia Elements
    - Interactive and Gamified eBooks

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